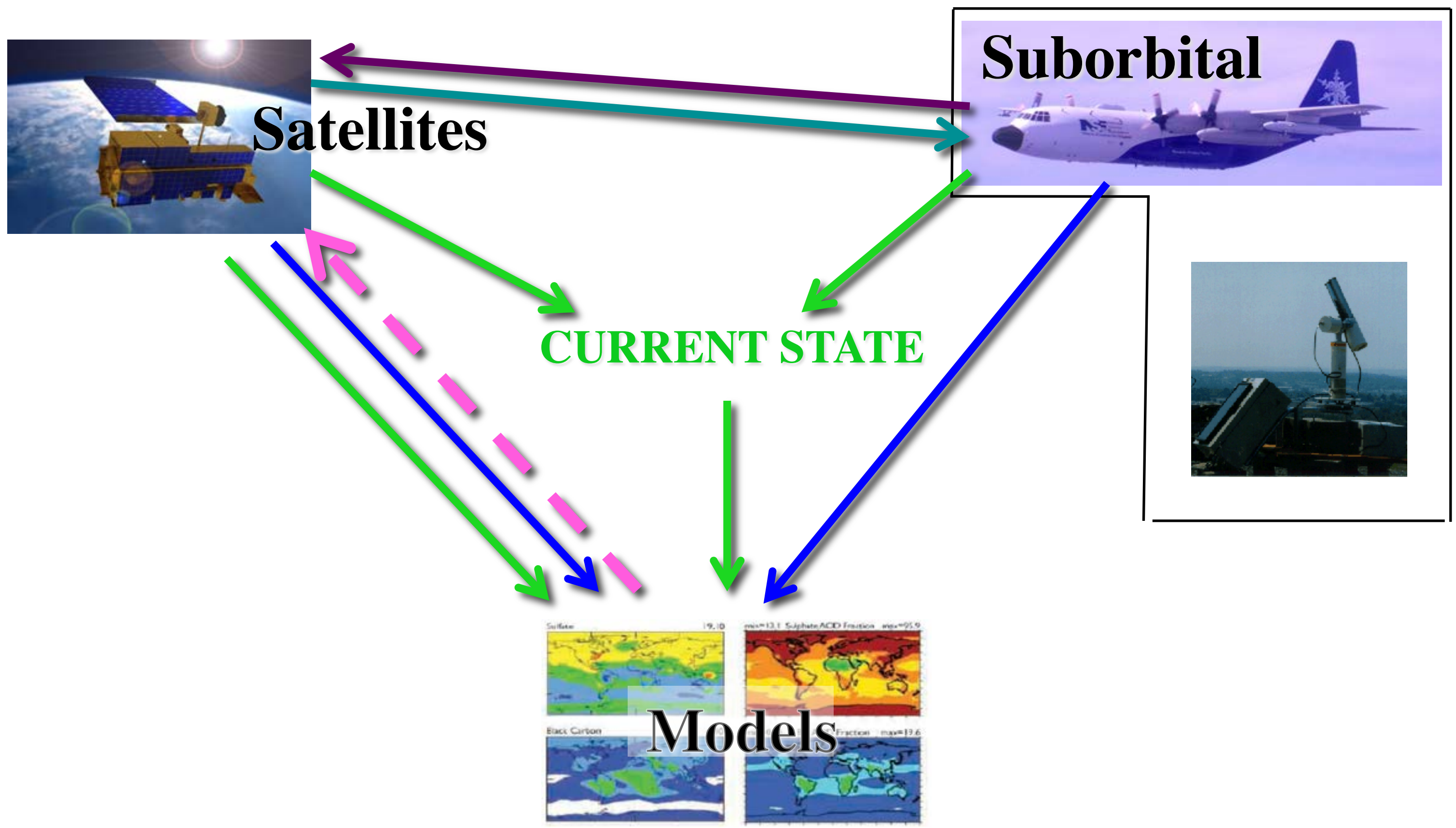
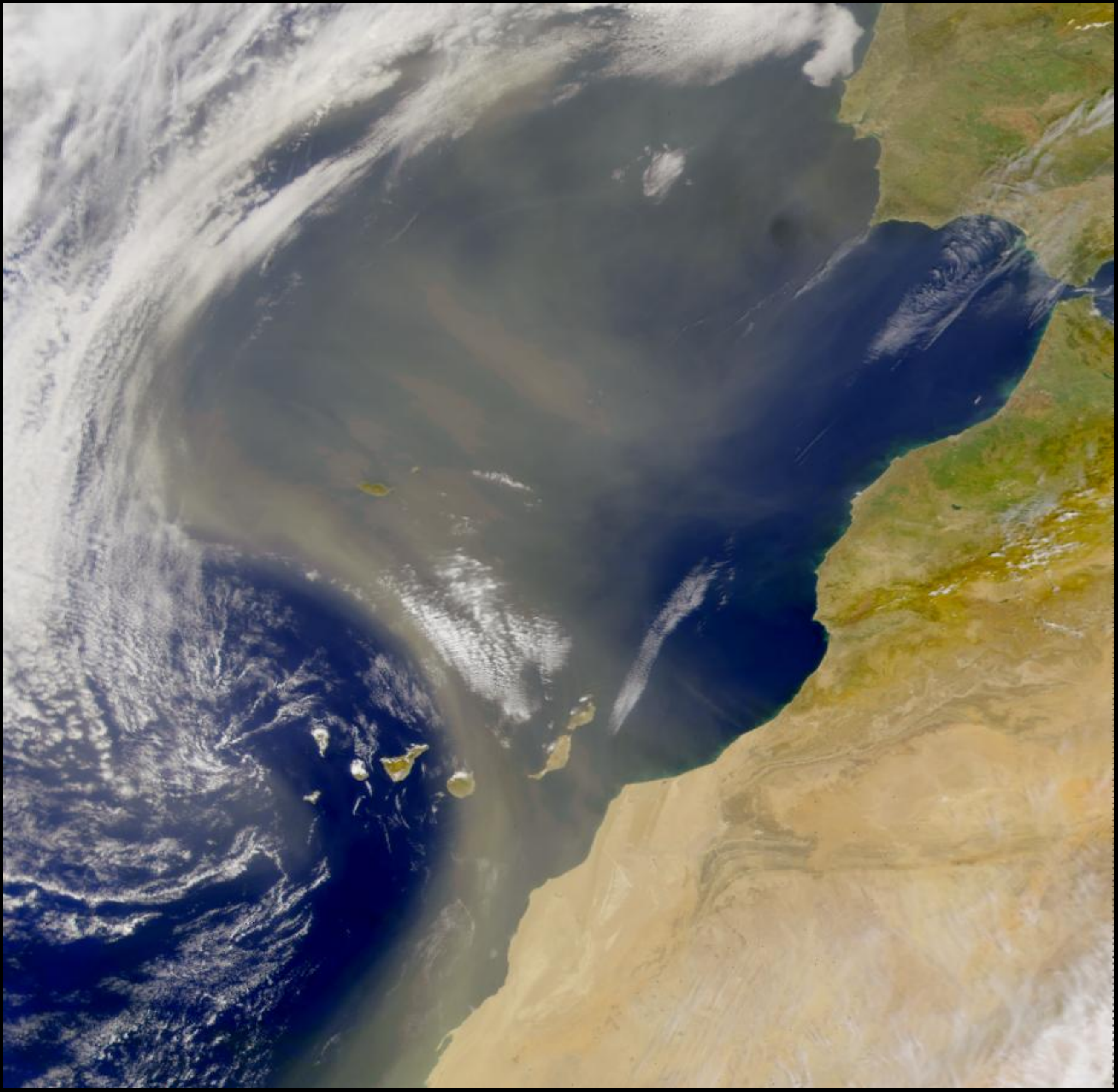
Aerosol Remote Sensing -- Application to Wildfire Smoke, Volcanic Plumes, Desert Dust, and Pollution Particles

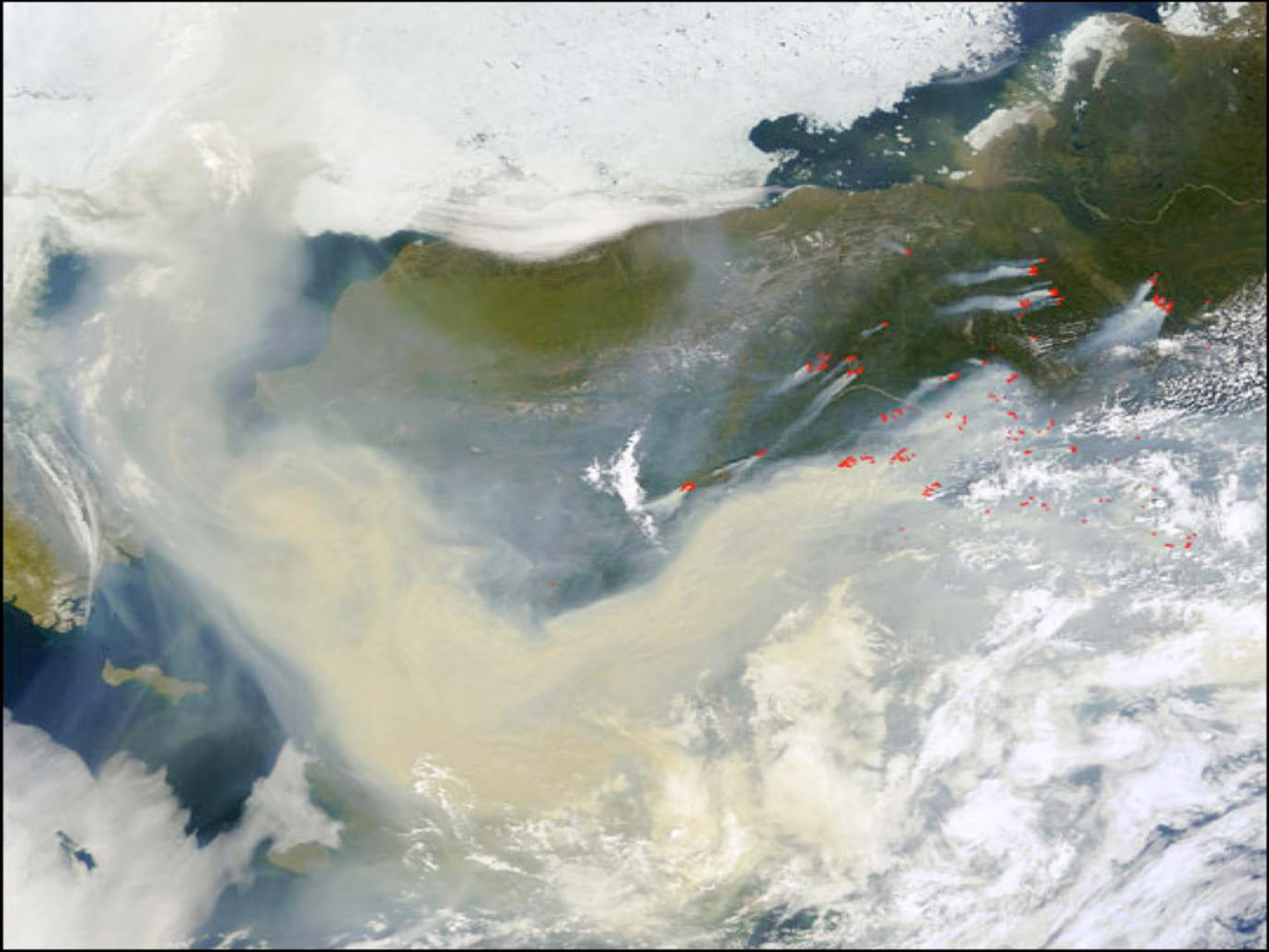
Ralph Kahn
NASA Goddard Space Flight Center



SeaWiFS – Sahara Dust over Canary Islands *06 March 1998*



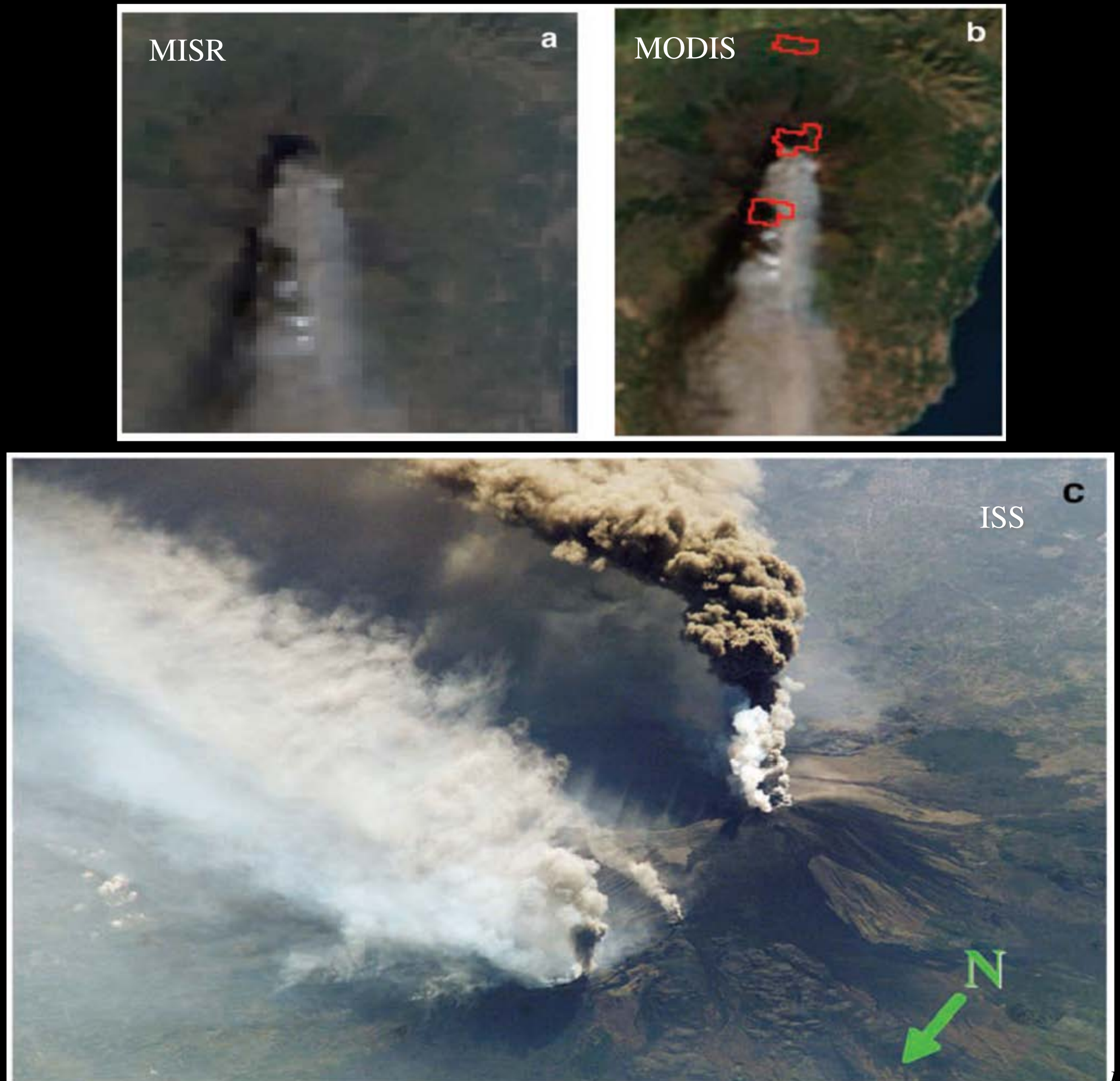
Phoenix Dust Storm 05 July 2011 Phoenix New Times

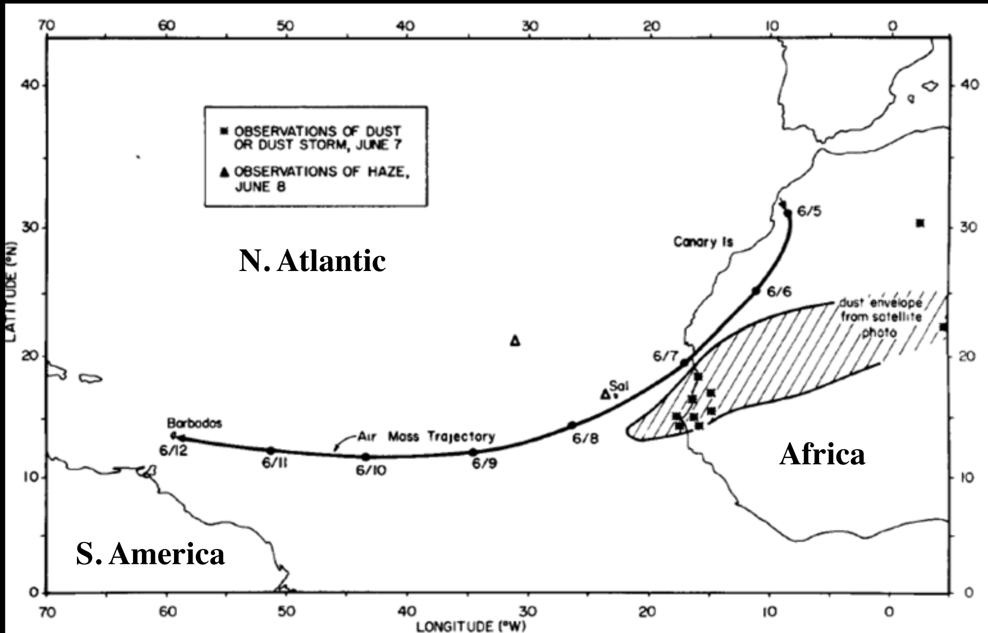


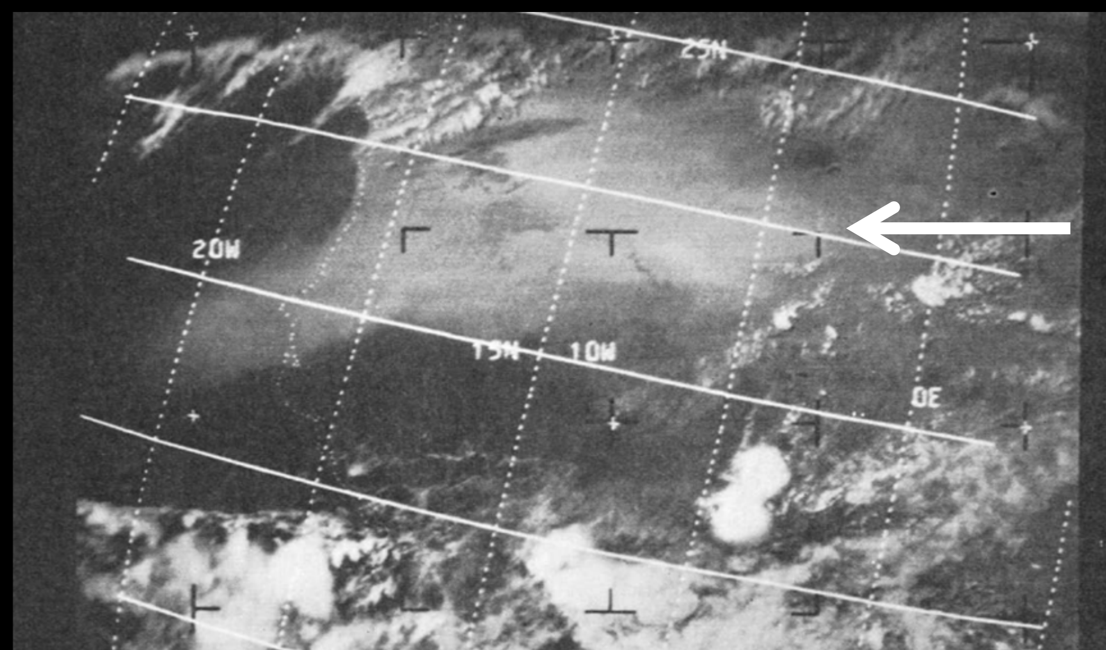
Smoke from Alaska fires
MODIS Image, July 1, 2004

Station Fire near JPL, Pasadena CA August-September 2010

Mt. Etna Plume Structure 27-30 October 2002

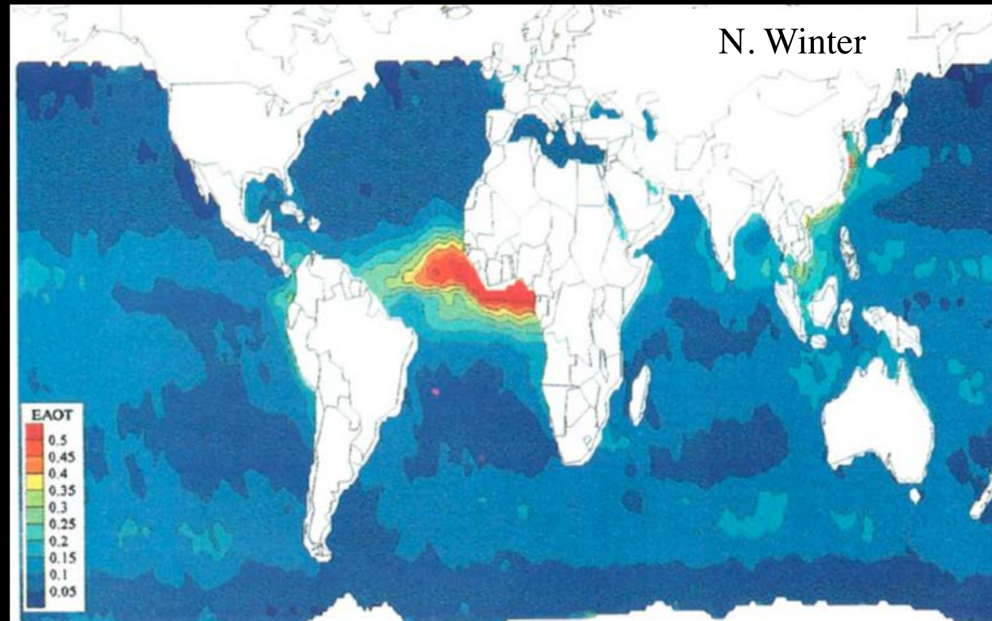


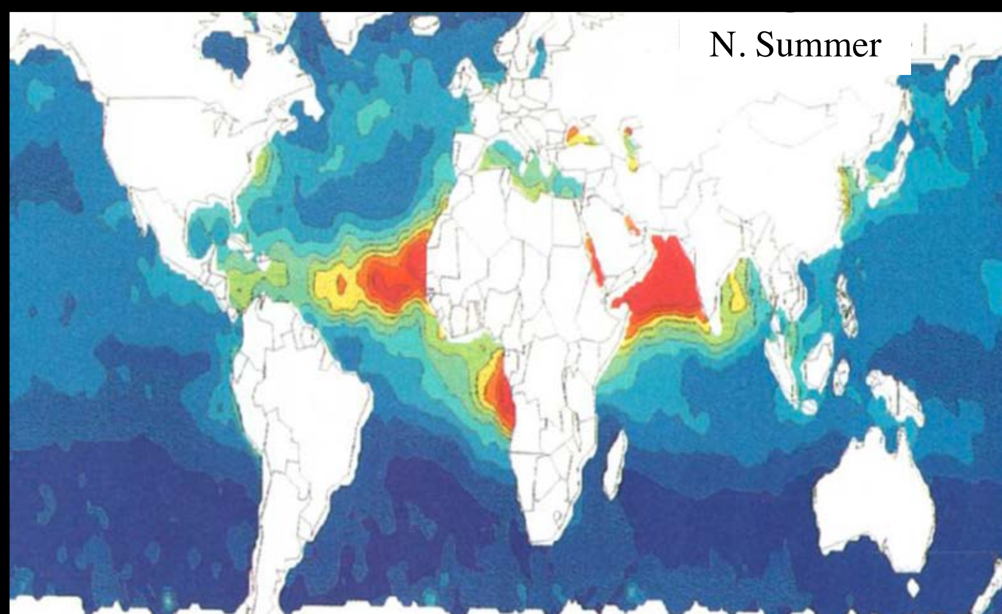




Saharan Dust Storm
8-day trajectory
Beginning 07 June 1967
ESSA 5 Satellite

Prospero et al., Earth & Planet. Sci. Let. 1970





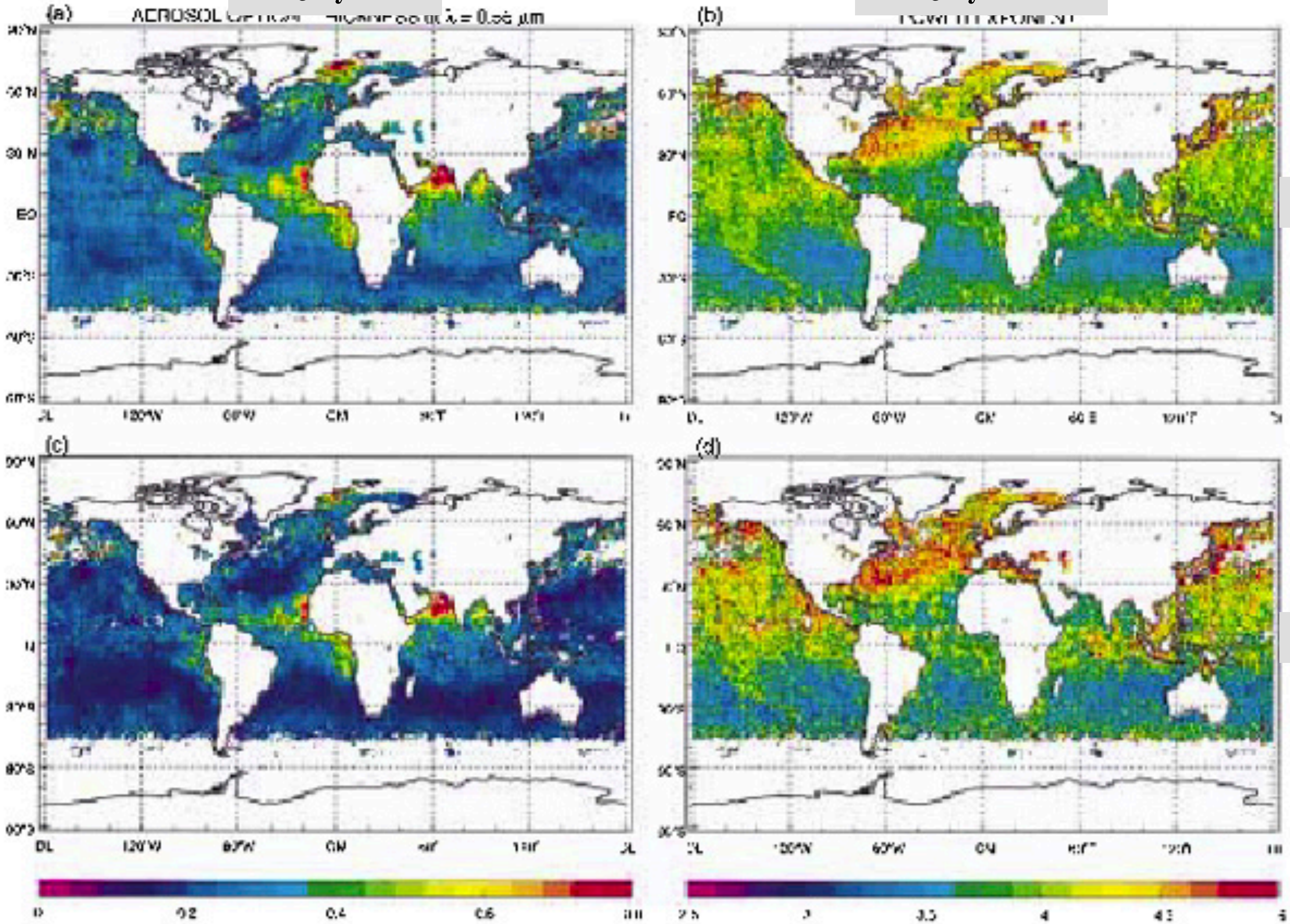
AVHRR
July 1989-June 1991
Aerosol Optical Depth

Husar, Prospero, & Stowe JGR 1997

AVHRR 2-Channel GISS AOT

τ -- July 1986

α -- July 1986



Cloud Screen 1

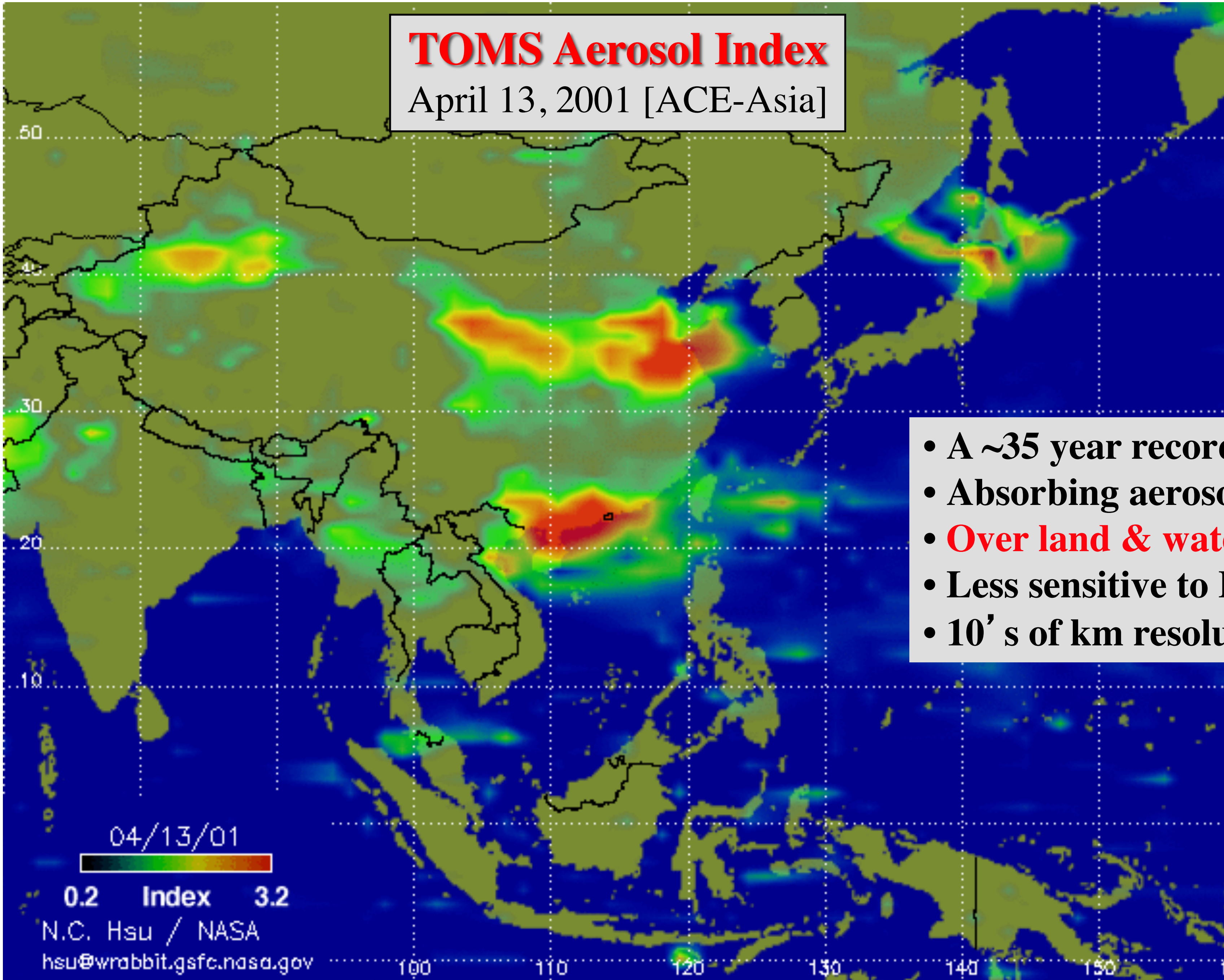
Cloud Screen 2

Fig. 6. (a) and (b) Monthly mean optical thickness (τ) and optical-thickness-weighted power exponent (α) for July 1986 derived with the benchmark atmosphere–ocean model and the standard ISCCP cloud-detection scheme. (c) and (d) As in panels (a) and (b) but with a modified cloud-detection scheme that retains only pixels with channel-5 temperatures warmer than the respective composite values.

Mishchenko et al., Appl. Opt. 1999

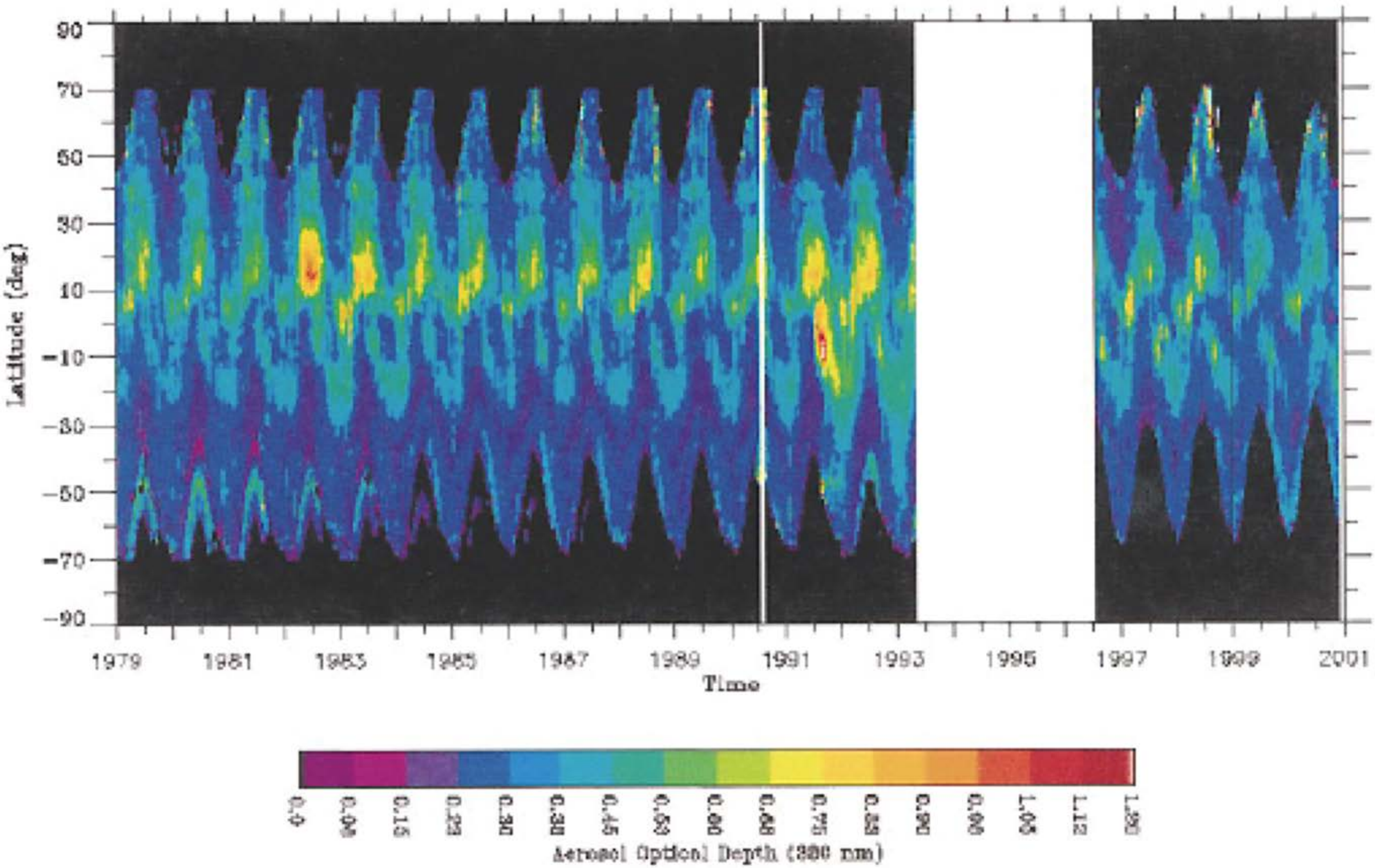
TOMS Aerosol Index

April 13, 2001 [ACE-Asia]



- A ~35 year record
- Absorbing aerosols
- Over land & water
- Less sensitive to BL
- 10’s of km resolution

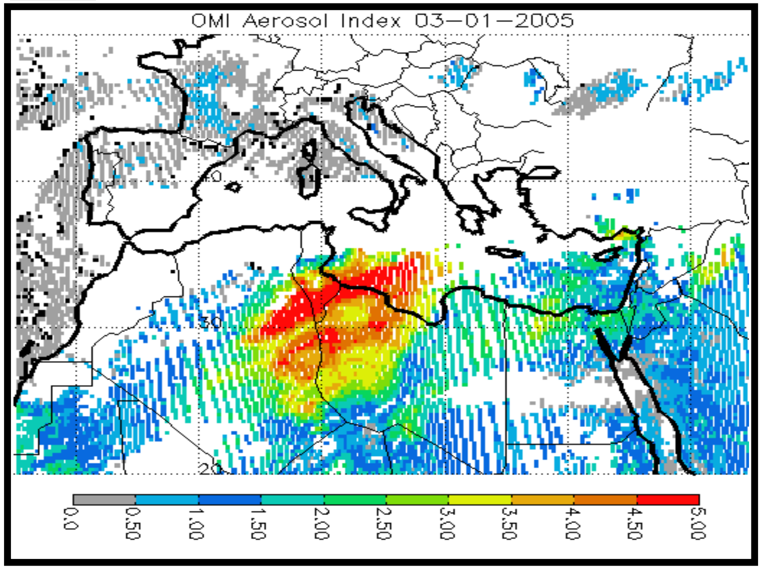
TOMS Aerosol Index
1979-2001 Weekly, Zonal, 1˚x1˚ Average Global Record



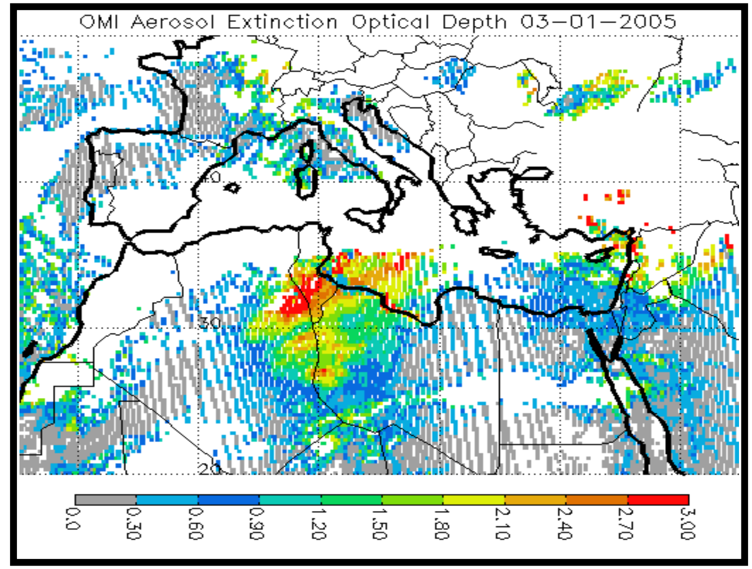
Torres et al, JAS, 2002

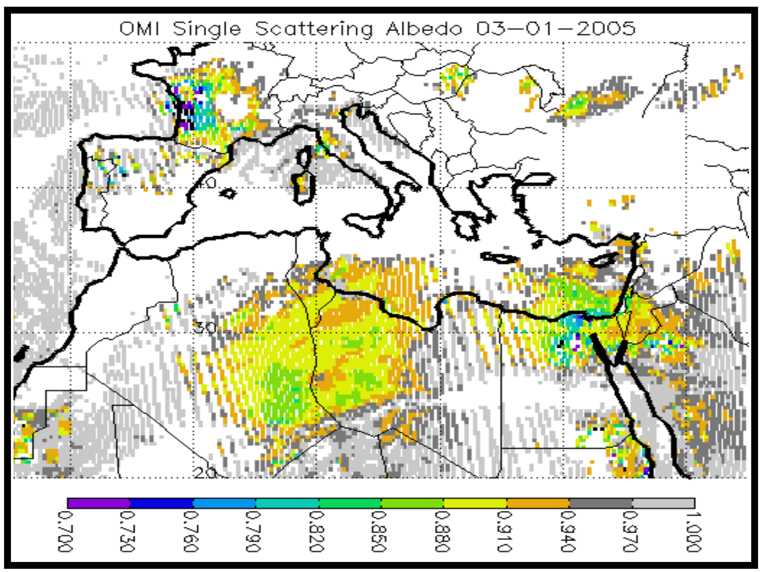
OMI Aerosol Products

AI

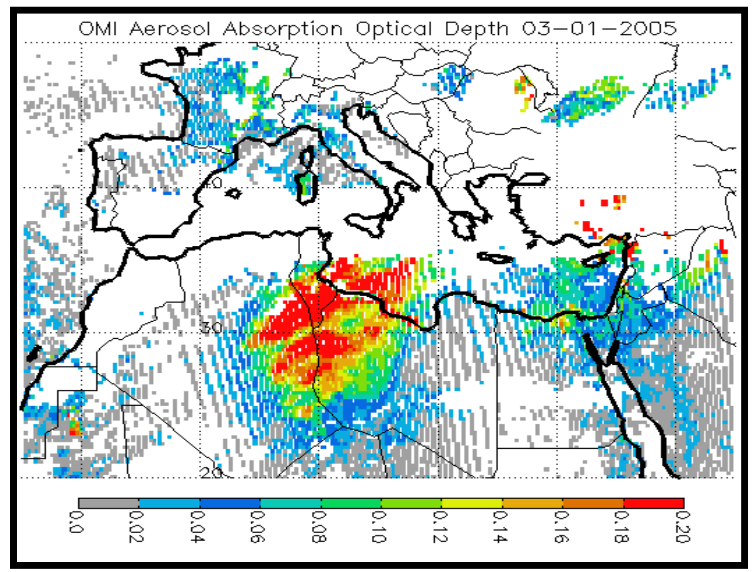


Extinction AOD





SSA



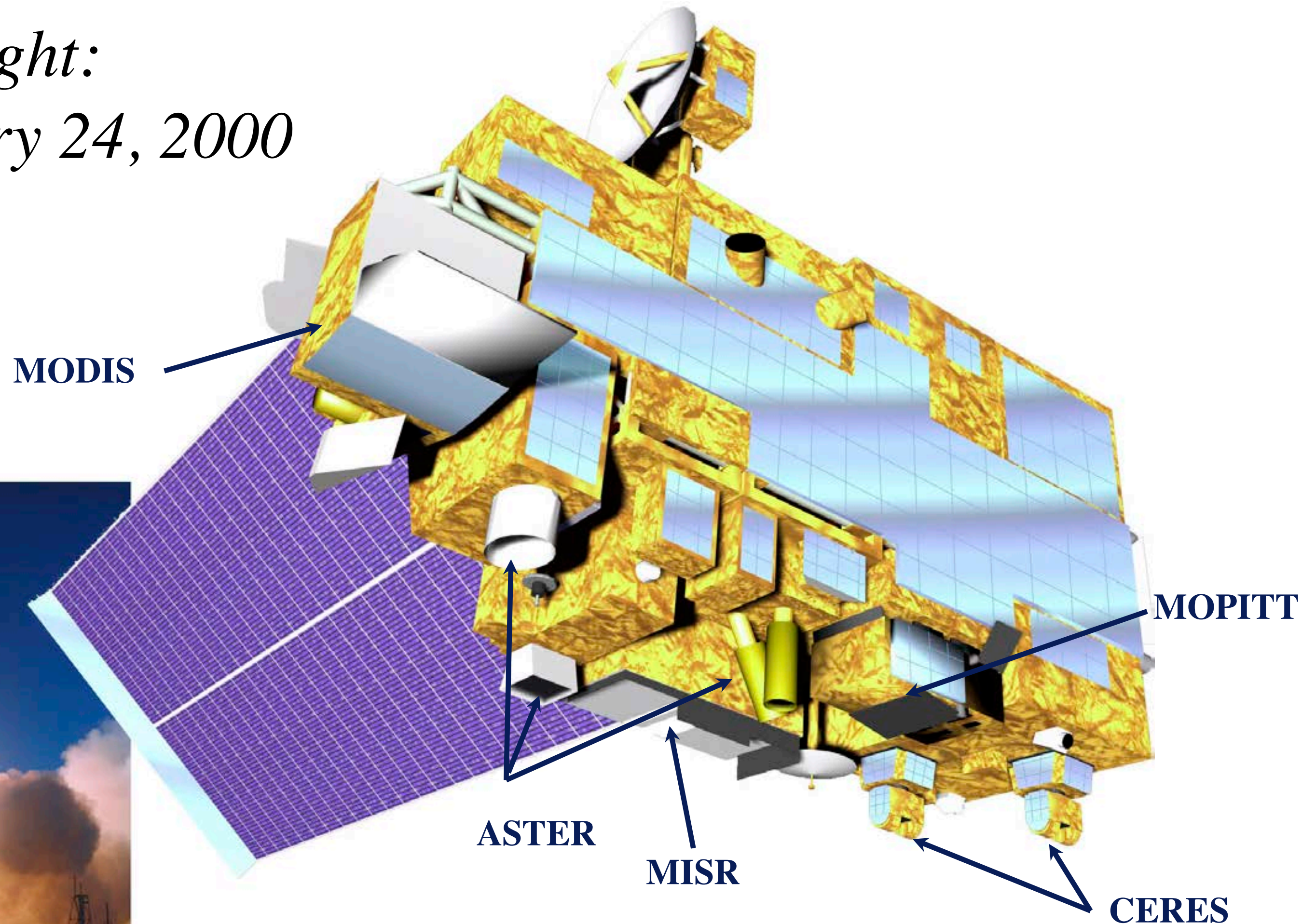
Absorption Optical Depth

March 01, 2005

From: Omar Torres

The NASA Earth Observing System's Terra Satellite

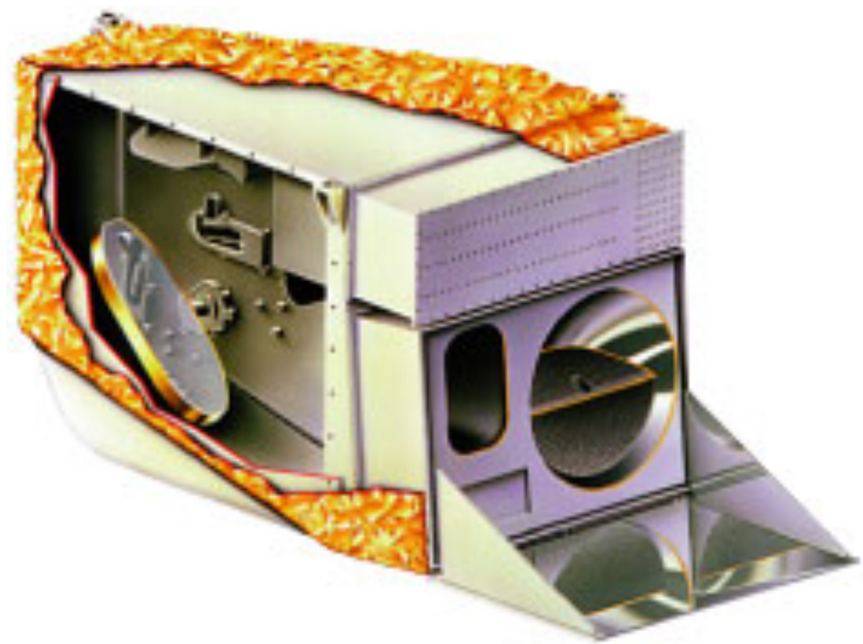
First Light:
February 24, 2000



Source: Terra Project Office / NASA Goddard Space Flight Center

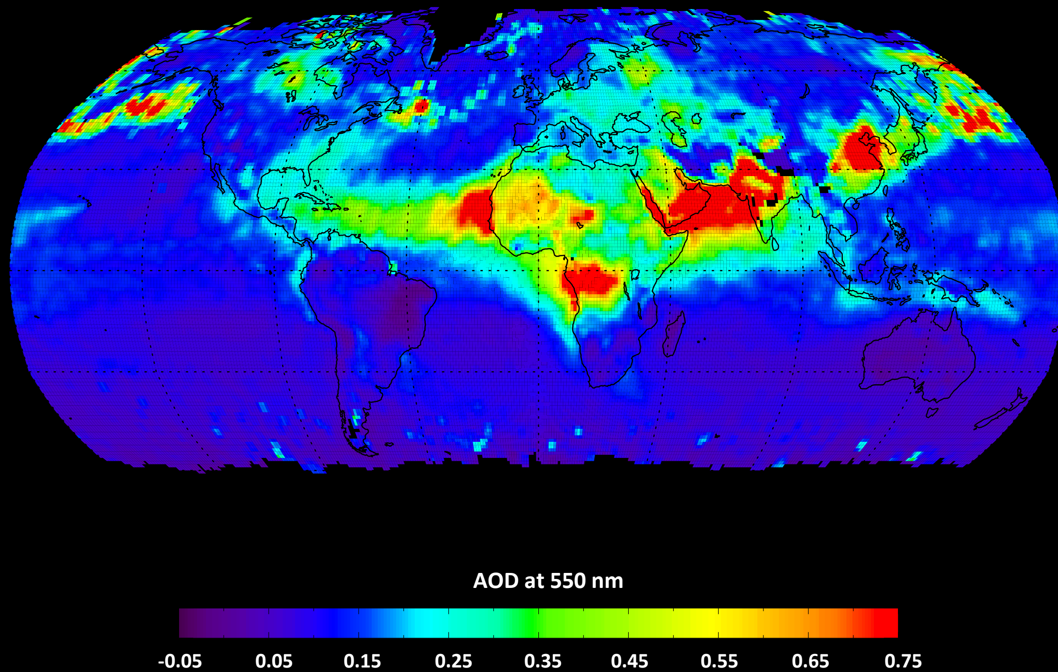
MODerate-resolution Imaging Spectroradiometer [MODIS]

- NASA, Terra & Aqua
  - launches 1999, 2001
  - 705 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 μm
  - cross-track scan mirror with 2330 km swath width
  - Spatial resolutions:
    - 250 m (bands 1 - 2)
    - 500 m (bands 3 - 7)
    - 1000 m (bands 8 - 36)
  - 2% reflectance calibration accuracy
  - onboard solar diffuser & solar diffuser stability monitor



Improved over AVHRR:
- Calibration
- Spatial Resolution
- Spectral Range & # Bands

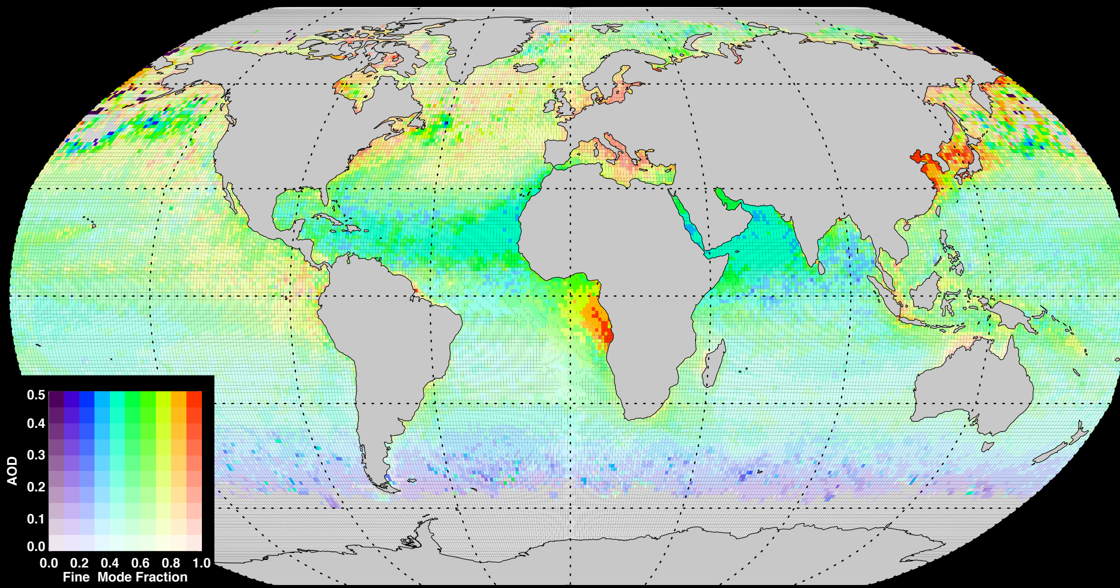
Source: MODIS Team, NASA/GSFC



Mid-Visible
AOD
“Dark Target” + “Deep Blue”

MODIS
July 2010
Monthly Average

- Water & some Land
- Globe ~ Every 2 days
- ~ 10:30 AM & 1:30 PM



- Fine/Coarse Ratio Over Water + AOD
- Sensitivity to PM10

MODIS Team, NASA Goddard Space Flight Center

Multi-angle Imaging SpectroRadiometer

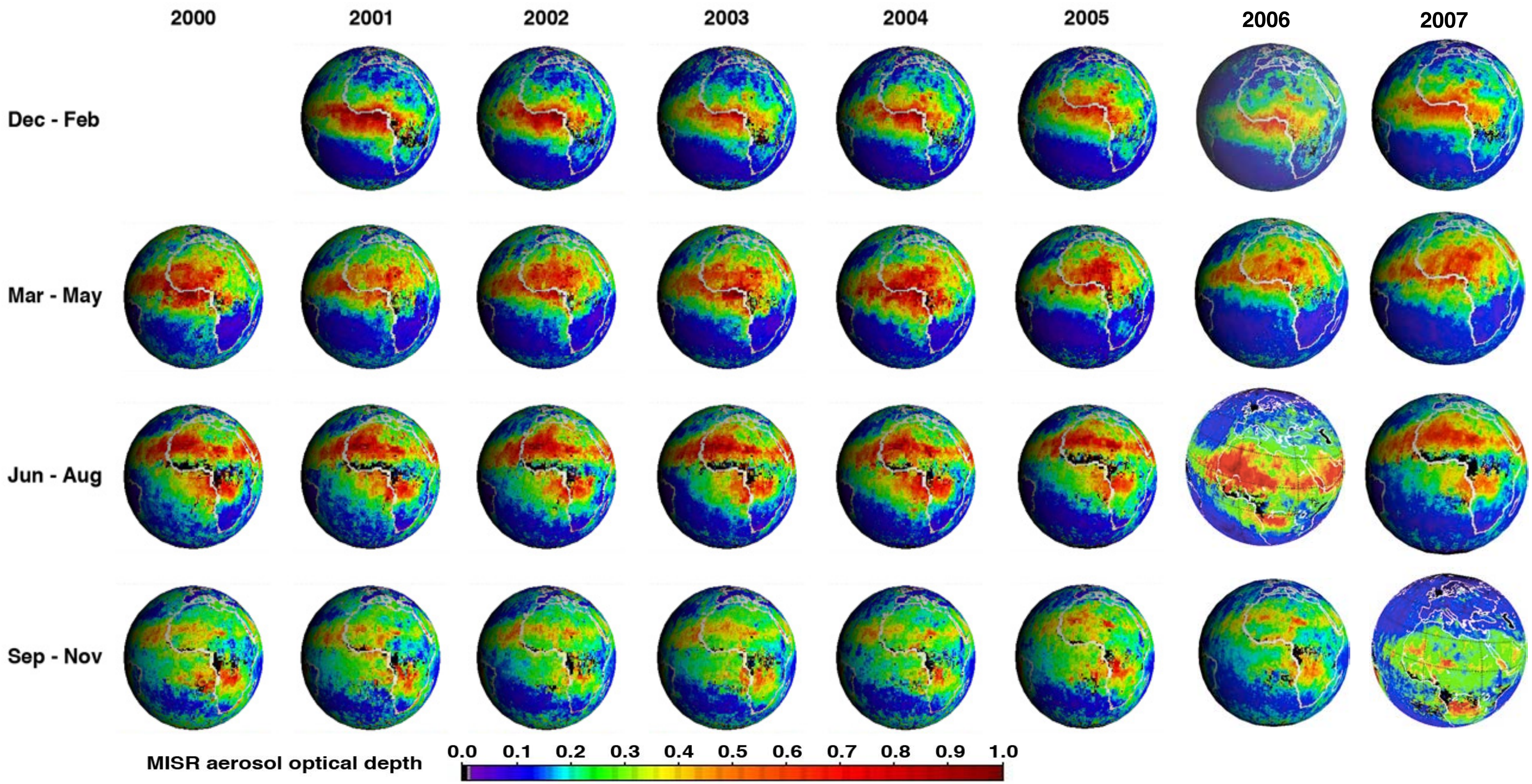
MISR

http://www-misr.jpl.nasa.gov

http://eosweb.larc.nasa.gov

- <u>Nine</u> CCD push-broom <u>cameras</u>
- <u>Nine</u> <u>view</u> <u>angles</u> at Earth surface: 70.5° forward to 70.5° aft
- <u>Four</u> <u>spectral</u> <u>bands</u> at each angle: 446, 558, 672, 866 nm
- Studies *Aerosols*, *Clouds*, & *Surface*

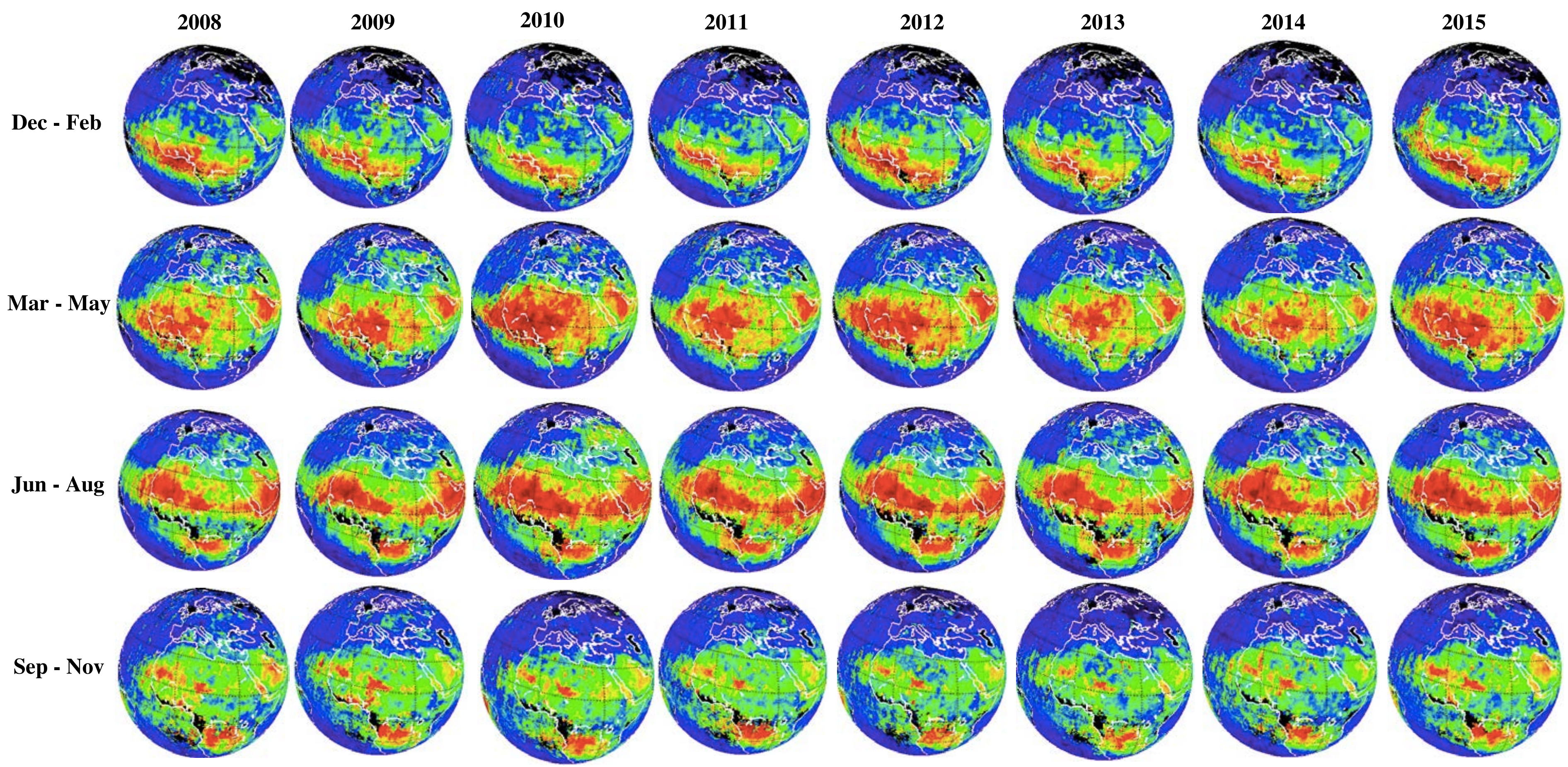
The *First Eight Years* of Seasonally Averaged Mid-visible **Aerosol Optical Depth** from MISR



…includes bright desert dust-source regions

MISR Team, JPL and GSFC

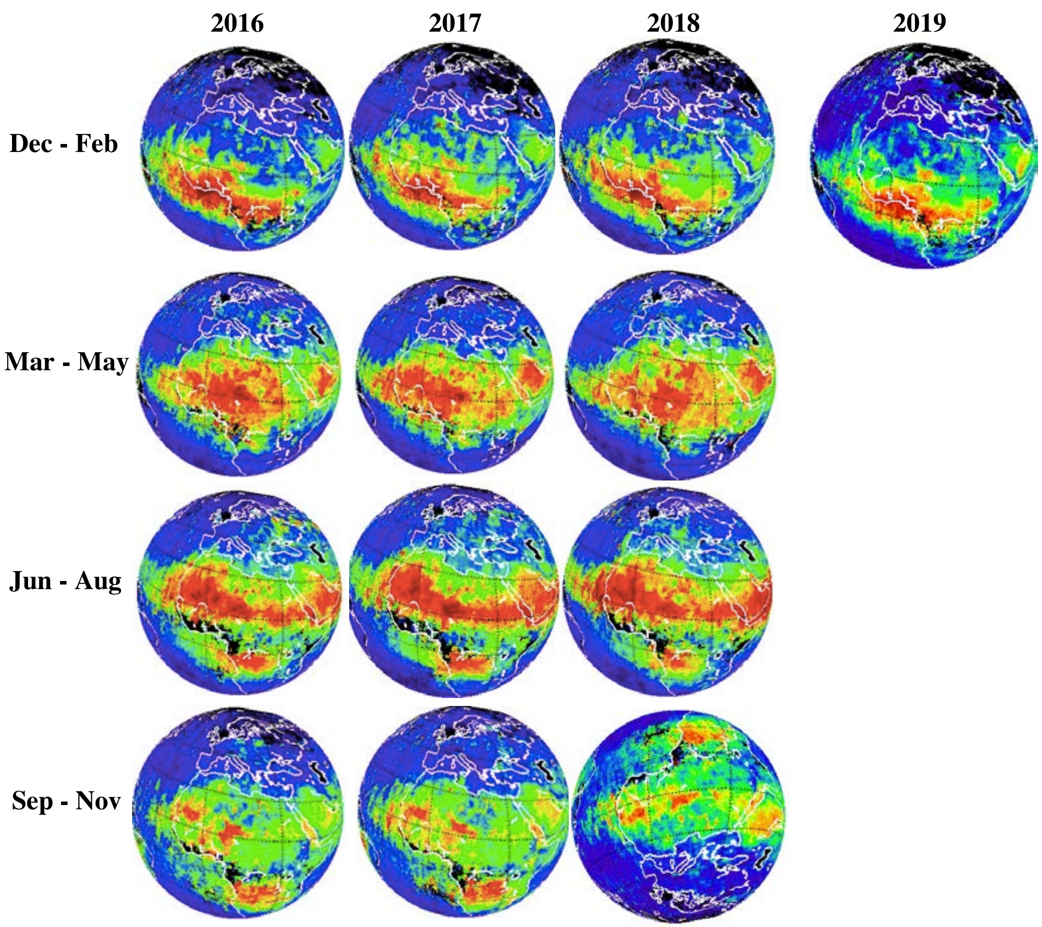
The *Second Eight Years* of Seasonally Averaged Mid-visible **Aerosol Optical Depth** from MISR



Provides ~ once-weekly global coverage…

MISR Team, JPL and GSFC

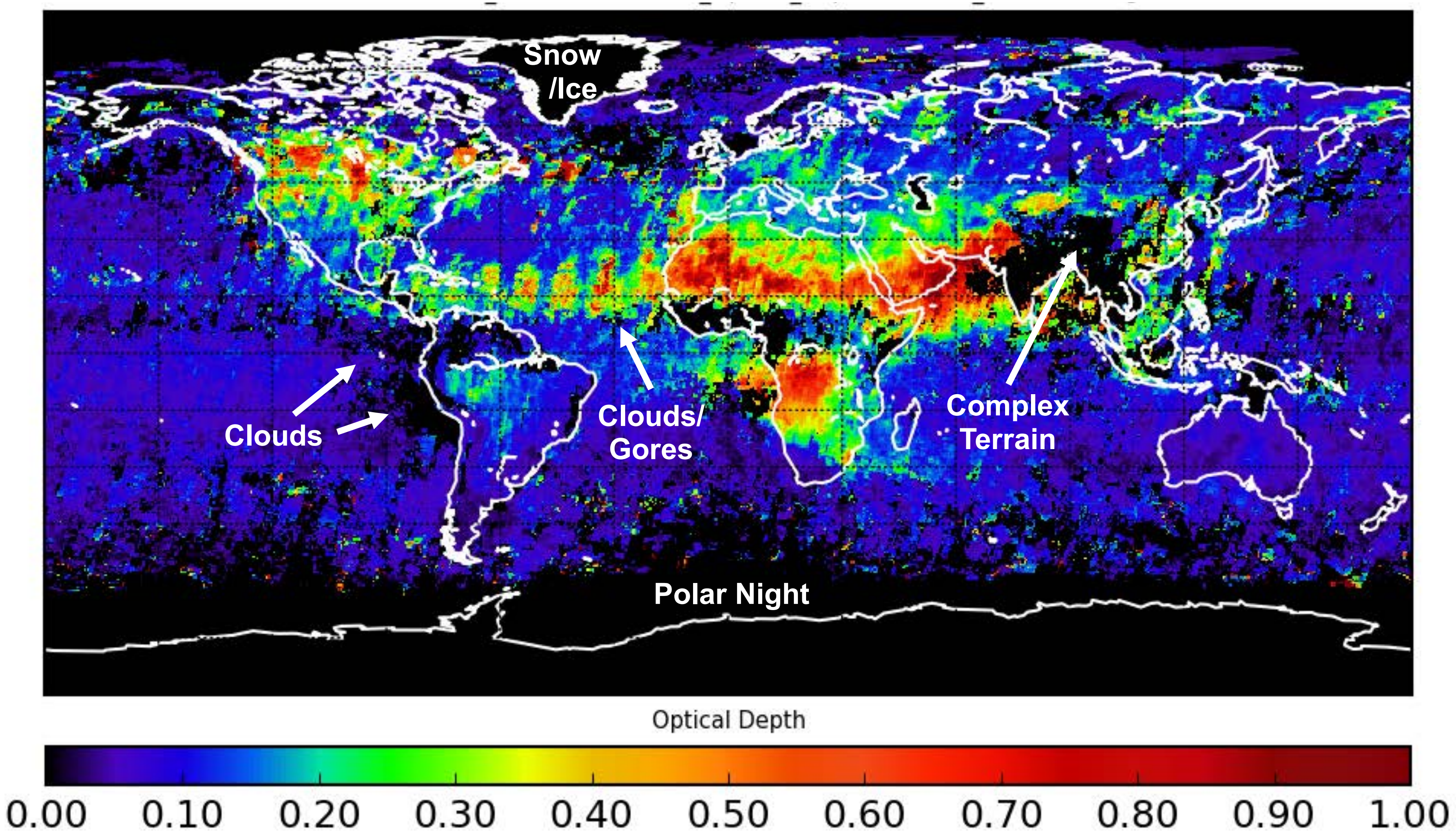
The *Most Recent* *Years* of Seasonally Averaged Mid-visible **Aerosol Optical Depth** from MISR



About 980 weekly global maps over 19+ years, and counting…

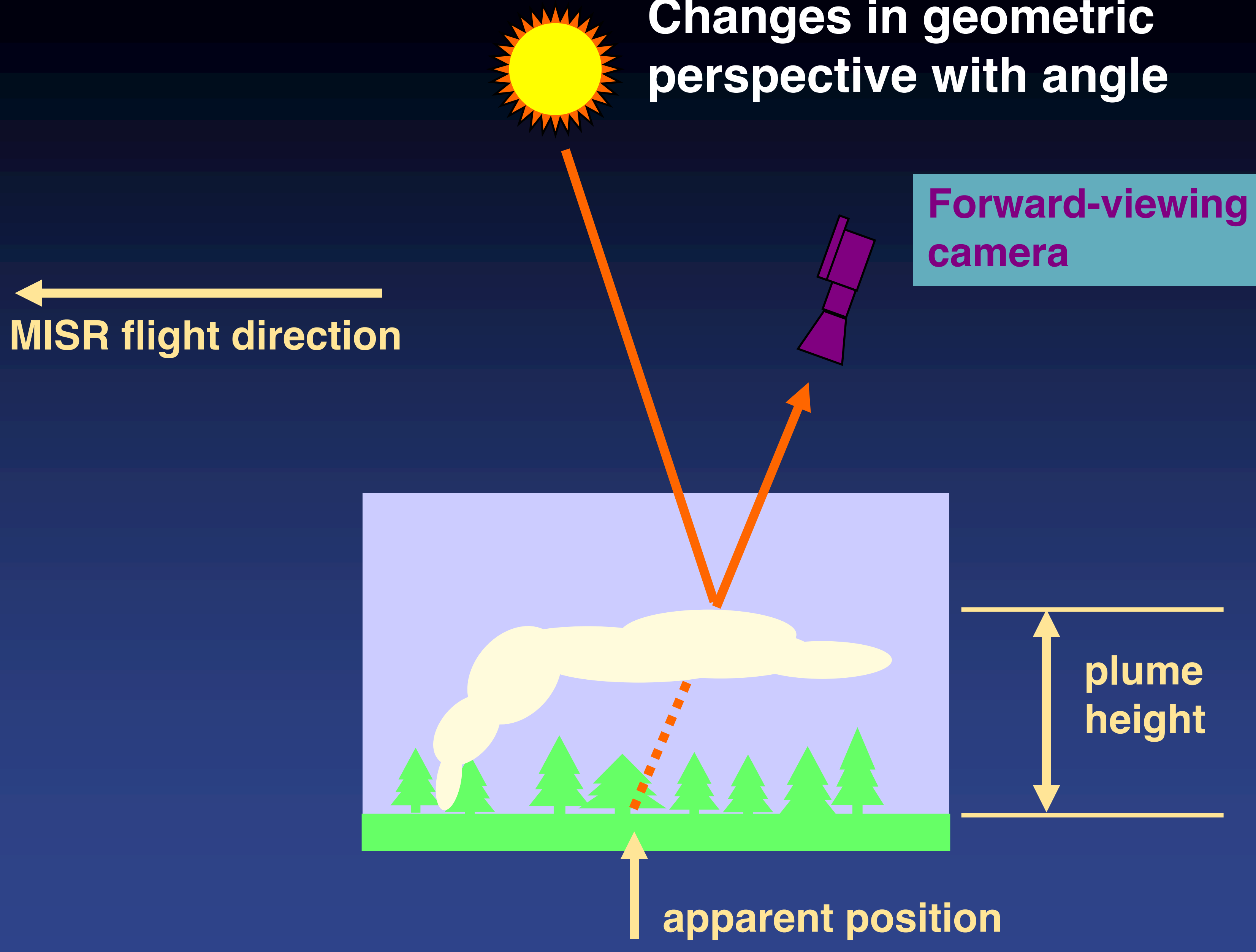
MISR Team, JPL and GSFC

Data Gaps – MISR *Aerosol Optical Depth* August 2018



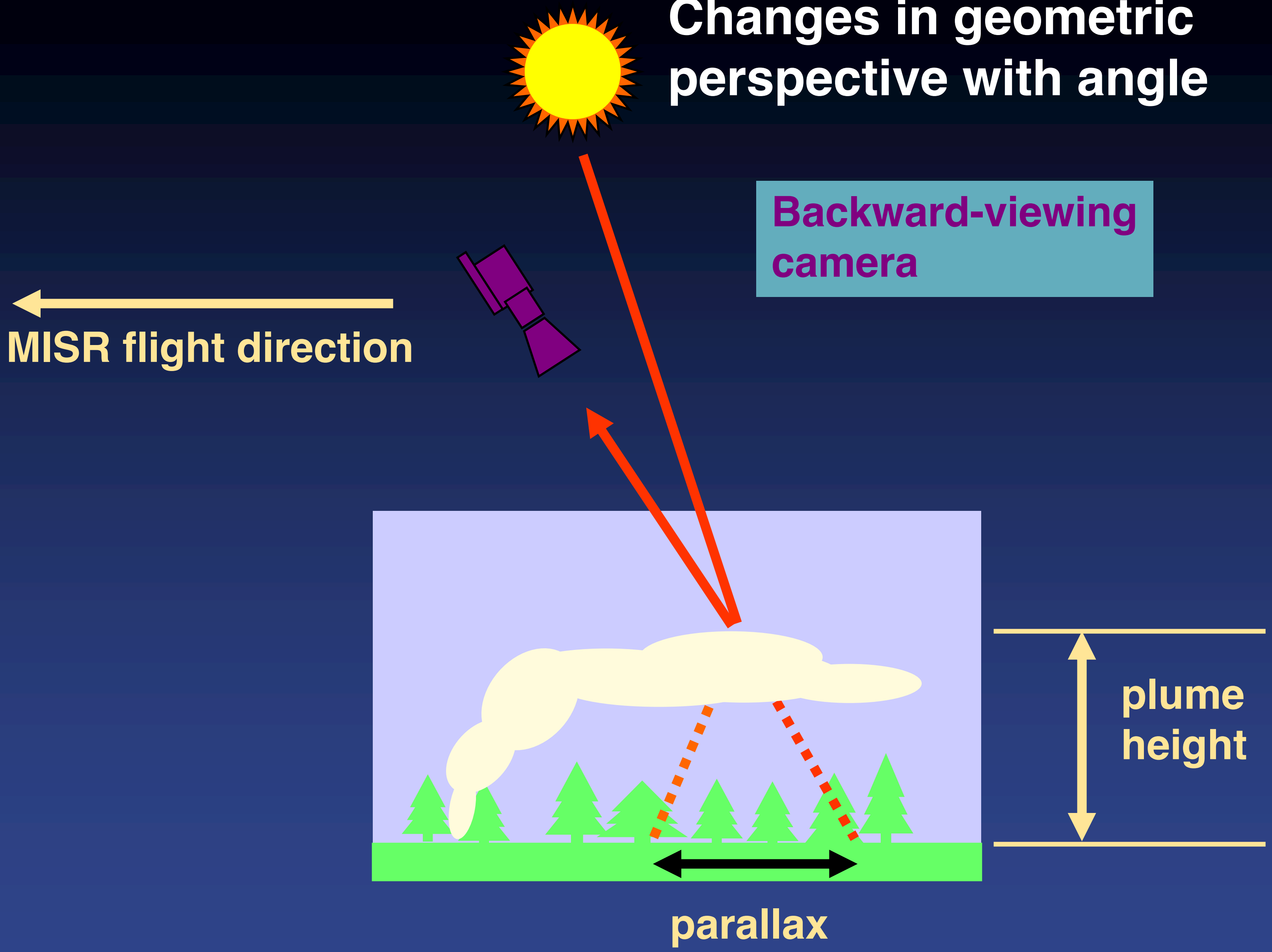
You can't always get what you want…

Changes in geometric perspective with angle



Diner 2003

Changes in geometric perspective with angle



Diner 2003

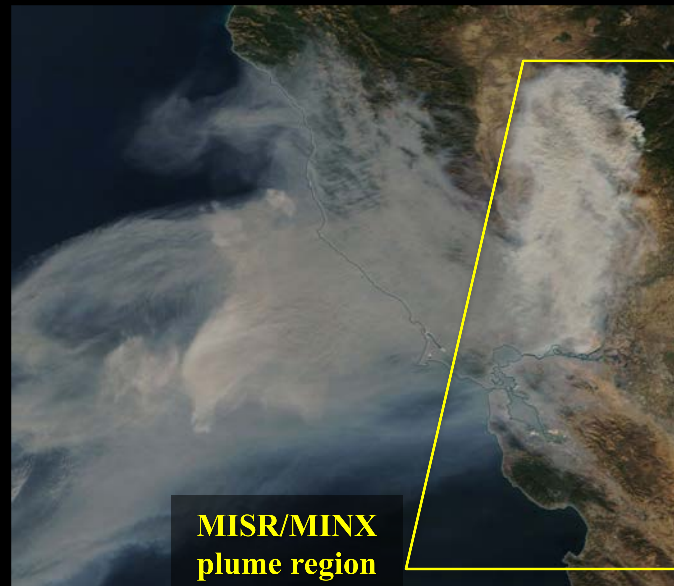
MISR Plume Heights – The California Camp Fire

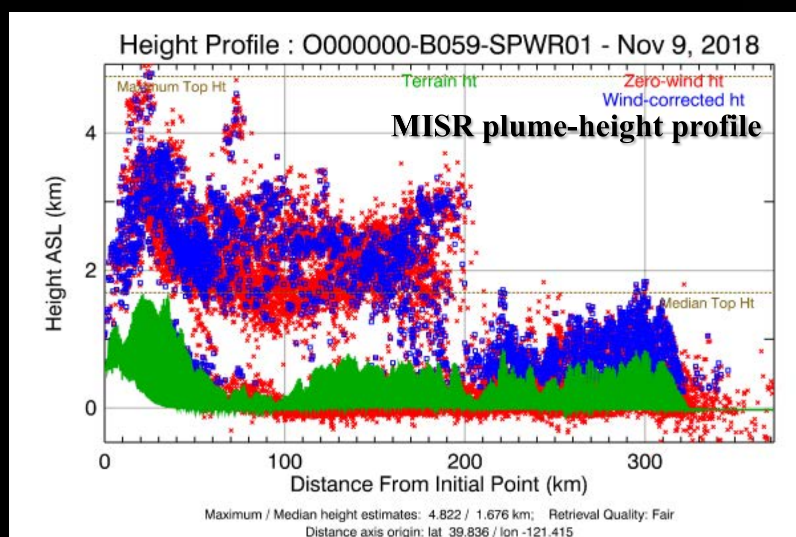
MISR Active Aerosol Plume-Height (AAP) Project 9 November 2018

CAMP FIRE

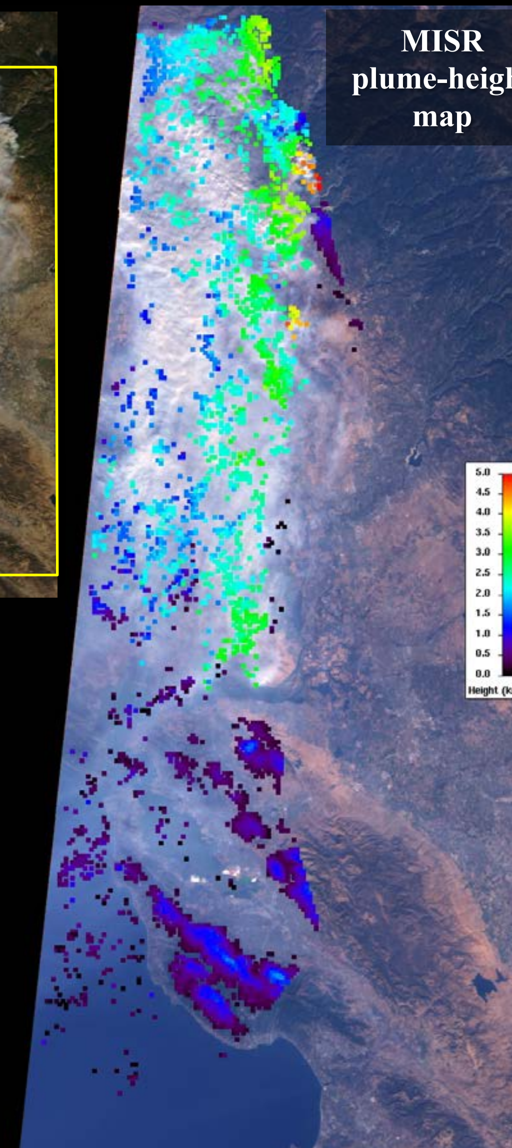
Origin: November 8, 2018
~39.81N, -121.44W

The Camp fire was the northernmost California fire MISR imaged on Nov. 9, and it was the deadliest fire in state history. It ***lofted smoke 2-3 km*** above the terrain, and some was ***transported over 300 km*** downwind. It is likely that the fires were sufficiently energetic to inject the smoke above ***the stable near-surface atmospheric boundary layer*** into the free troposphere. The plume descended to ***~1 km*** as it moved south and west and approached the ocean.





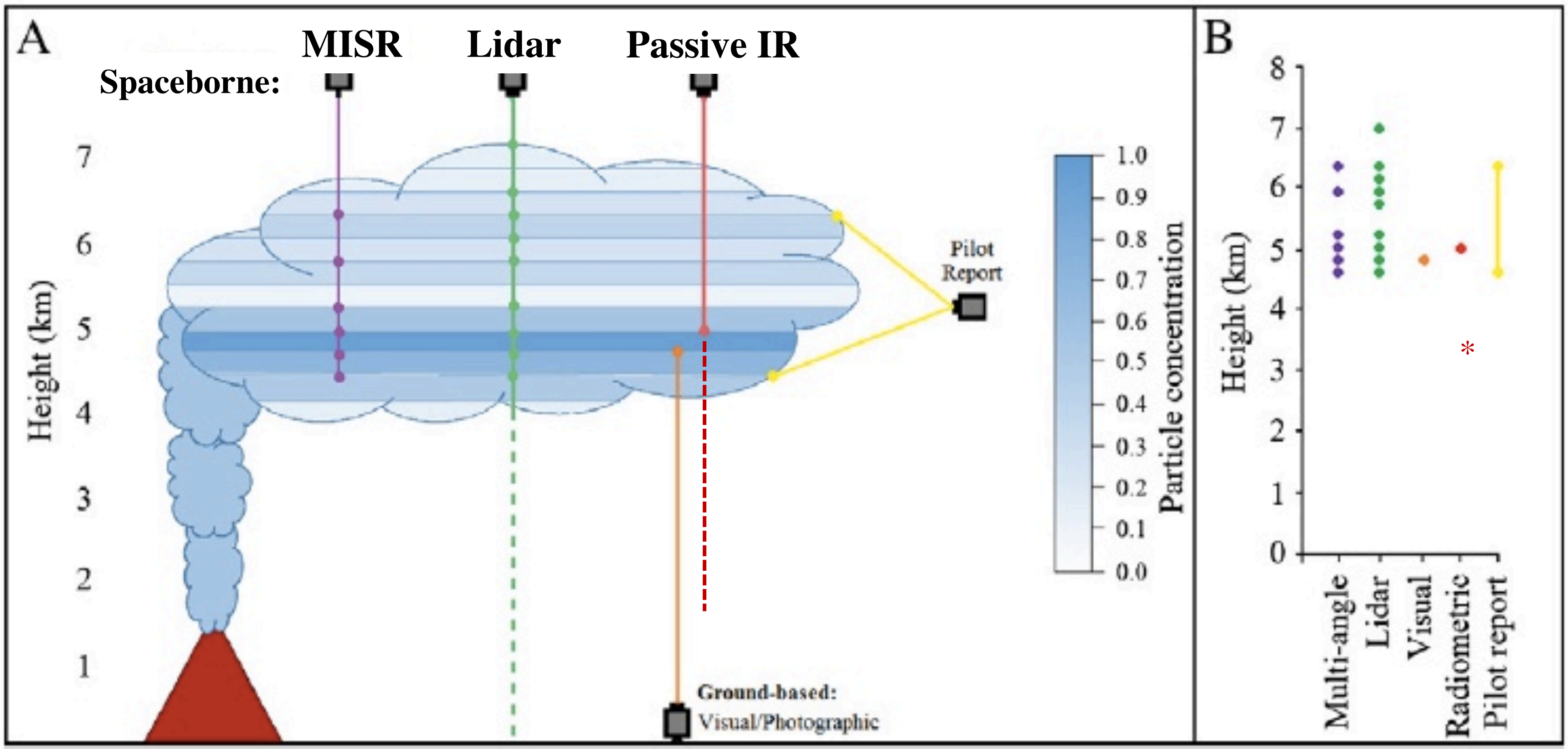
Red = zero-wind height
Blue = wind-corrected height
Green = surface elevation



V. Flower, R. Kahn, J. Limbacher / NASA GSFC

MISR Plume Heights – In Context

The MINX algorithm captures the elevation of max. horizontal spatial contrast

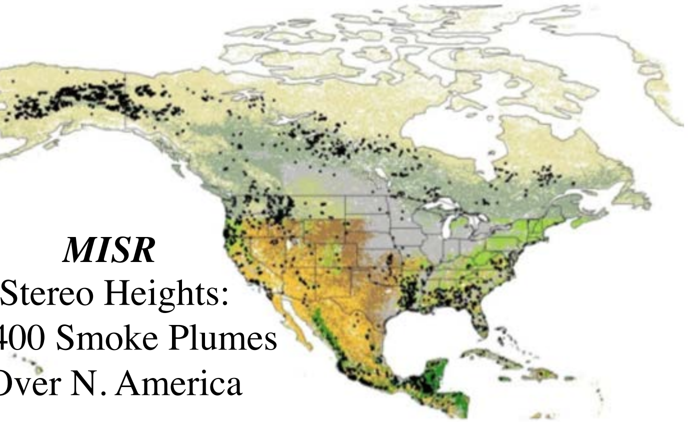


MINX usually retrieves a distribution of heights.
Median or Mean height? Pixel-count or AOD weighted?

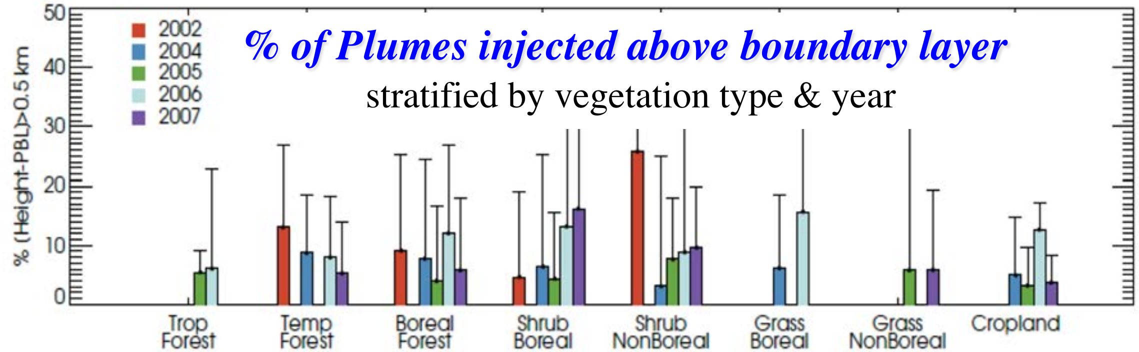
Flower & Kahn, J. Volc. 2017

Wildfire Smoke *Injection Heights* & *Source Strengths*

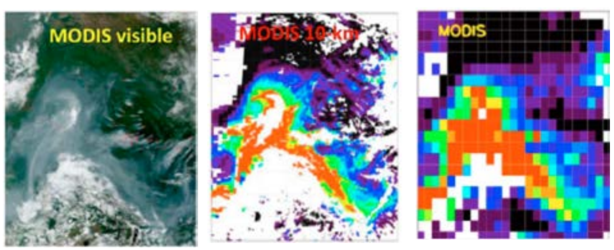
[These are *the two key parameters* representing aerosol sources in climate models]



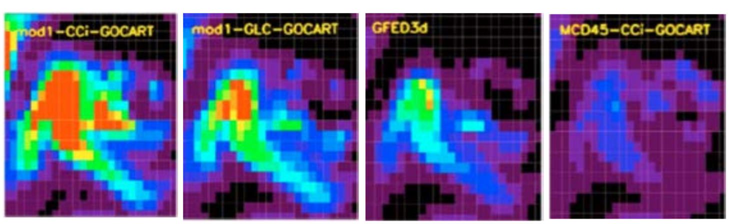
MISR
Stereo Heights:
~3400 Smoke Plumes
Over N. America



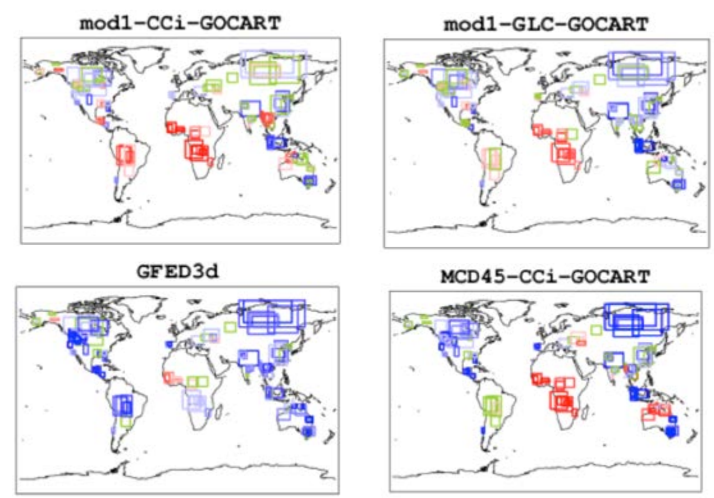
Val Martin et al. ACP 2010



MODIS Smoke Plume Image & Aerosol Amount Snapshots



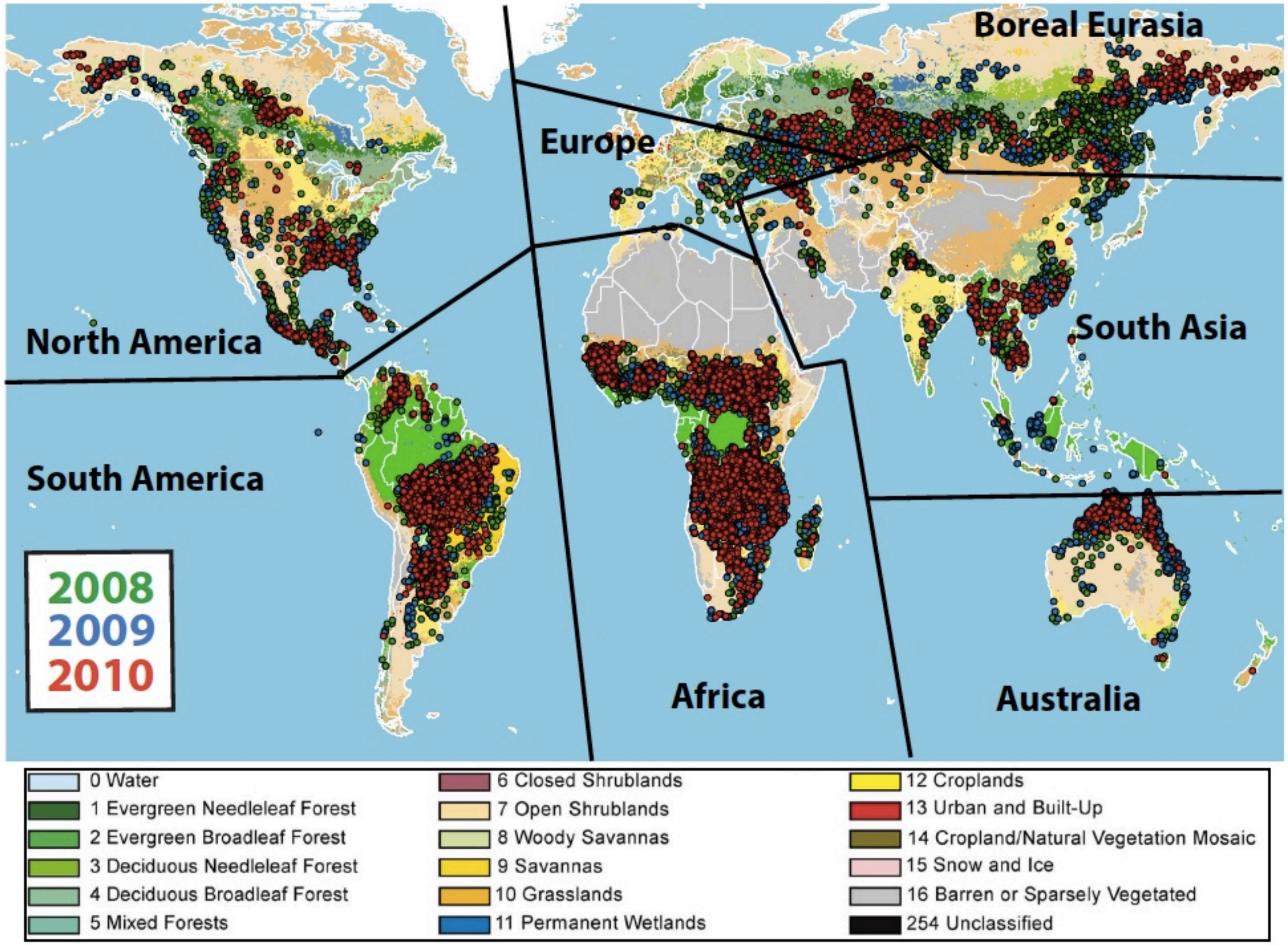
GoCART Model-Simulated Aerosol Amount Snapshots
for *Different Assumed Source Strengths*



Different Techniques for *Assuming Model Source Strength*
Overestimate or ***Underestimate*** Observation
Systematically in Different Regions

Petrenko et al., JGR 2012

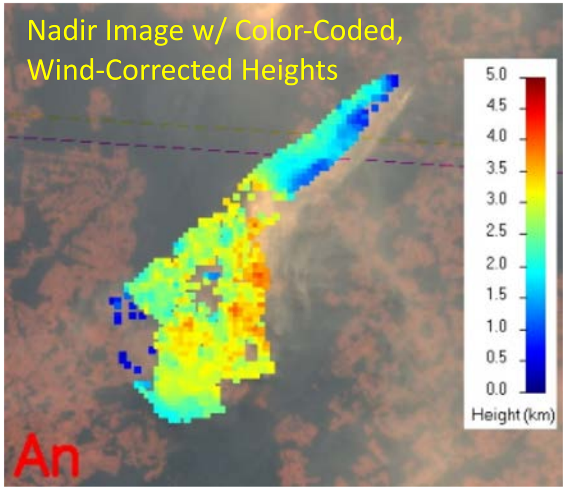
Biomass Burning Experiment *PHASE 2*:
Fire Emission Injection Heights



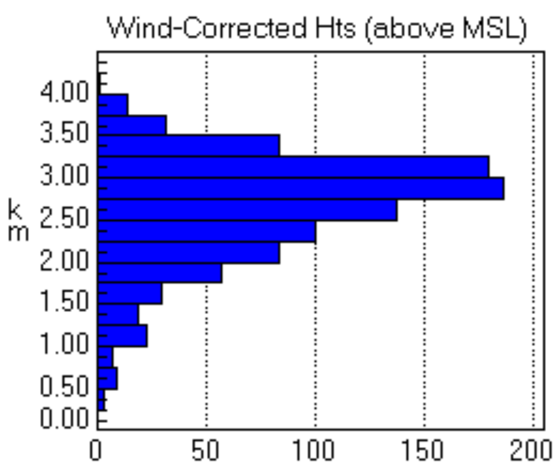
- About ***23,000 smoke plumes*** digitized 2008-2010 (~13,000 for 2008)
- Each plume is Operator-Processed using ***MINXv4.0***, and Quality Controlled
- For N America, ≥ ***4% - 12%*** of plumes are injected above the PBL; Boreal Forest **18%**
- Raw, graphics and summary files, and documentation are ***available on-line:***
  https://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes2/

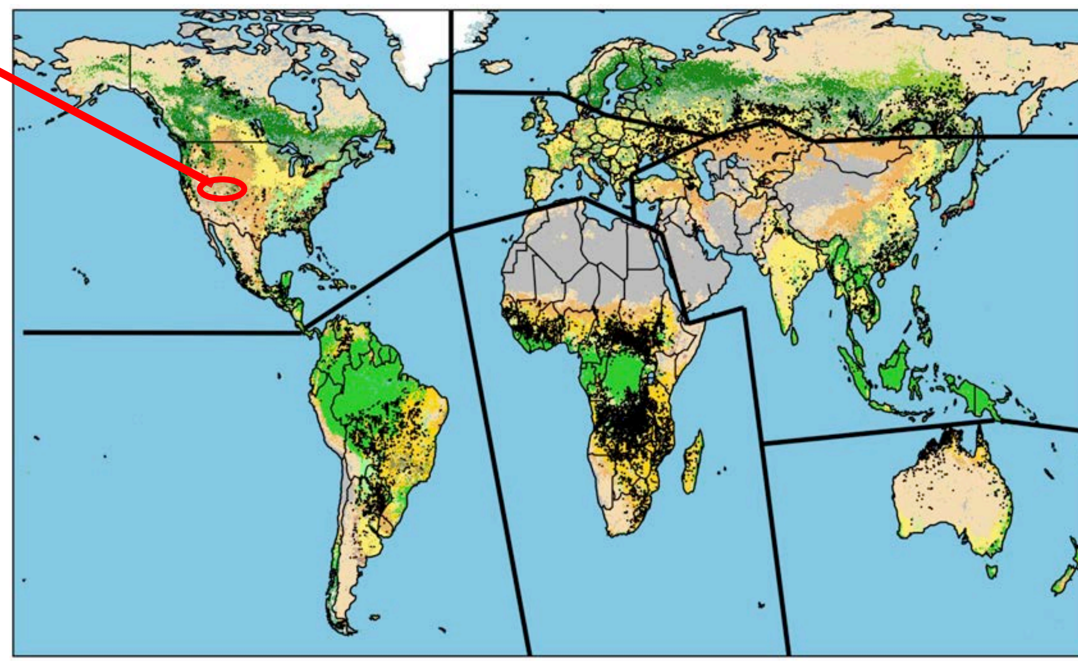
Val Martin et al., Remt. Sens.2018

Biomass Burning Experiment *PHASE 2*: *Fire Emission Injection Heights*



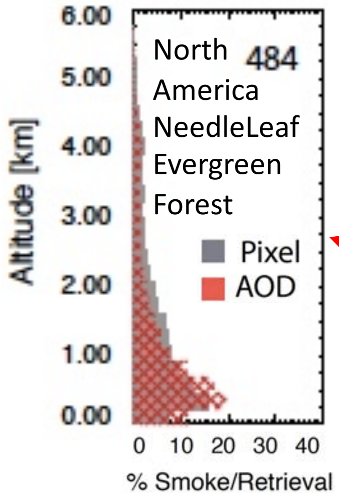
- Heights at ***1.1 km Horizontal*** res., ***~250-500 m Vertical*** res.
- Keyed to the ***Elevation of Maximum Spatial Contrast***
- Parallax is corrected for proper motion (***Wind Correction***)
- Missing AOD filled w/ ***max***; missing height w/***statistical dist***.
- Both ***Pixel-weighted*** and ***AOD-weighted*** profiles derived
- Height histogram gives some ***Indication of Vertical Extent***

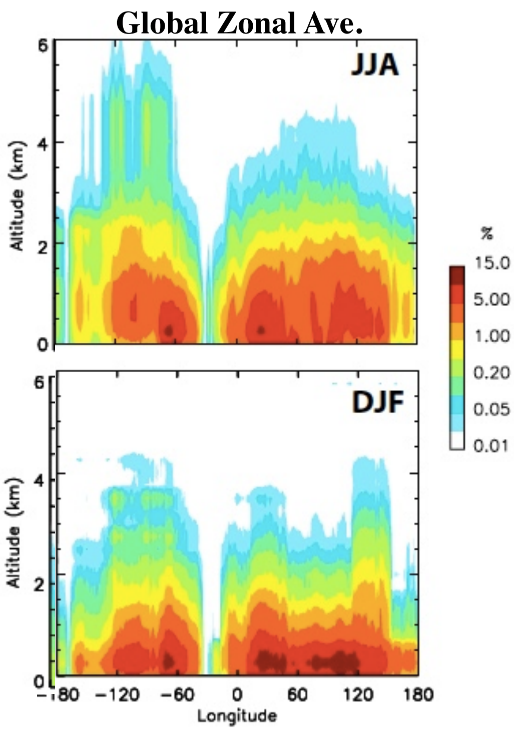


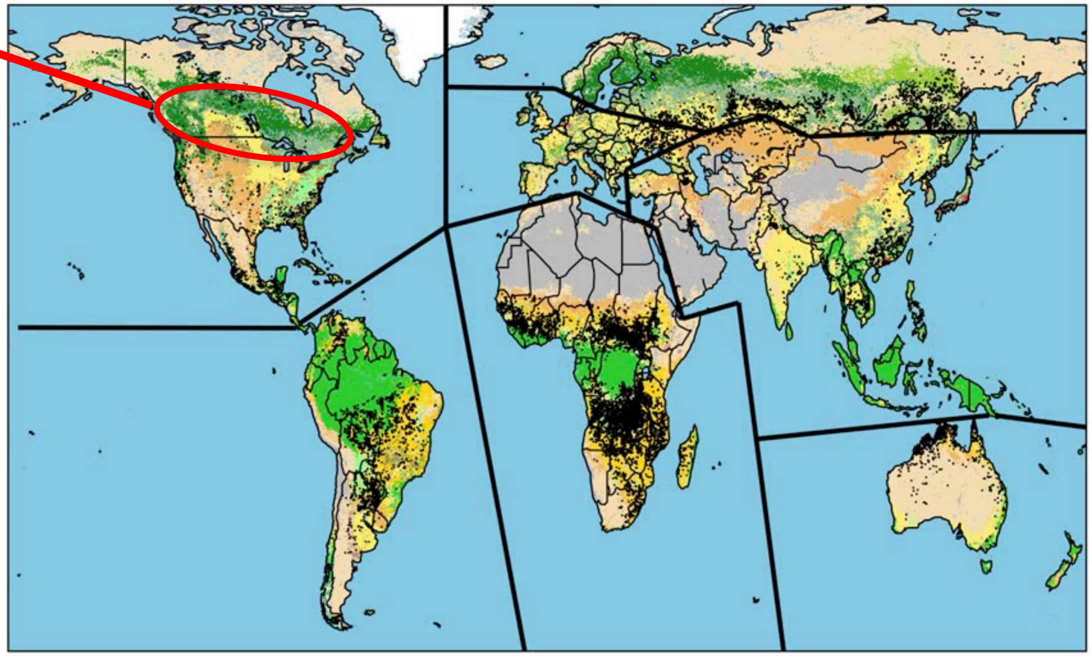


Val Martin et al., Remt. Sens. 2018

Biomass Burning Experiment *PHASE 2*: *Fire Emission Injection Heights*





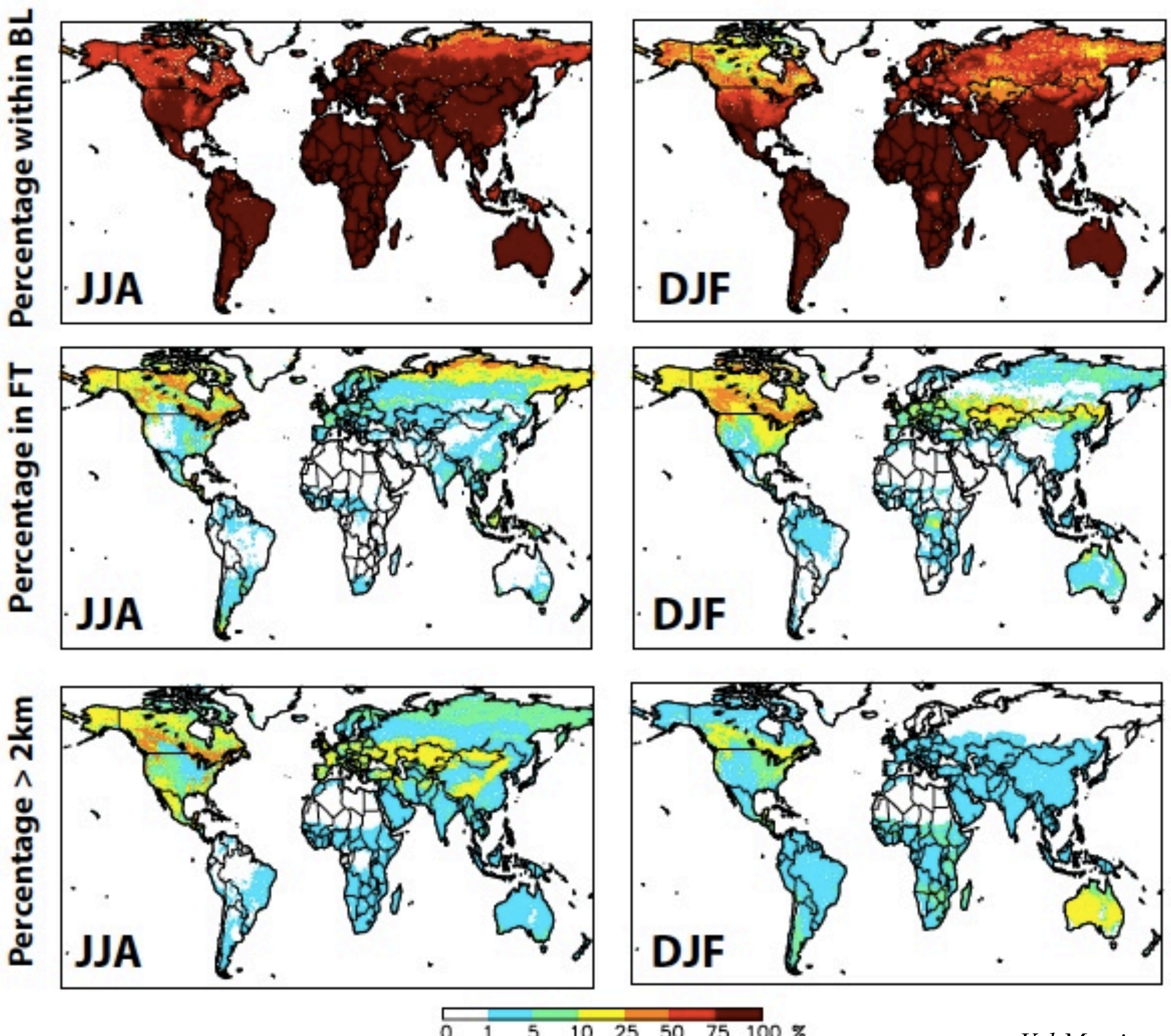


- Fire emissions are ***Stratified by Altitude***, ***Region***, ***Ecosystem***, & ***Season***
- The cases in each stratum are ***Averaged*** to produce a statistical summary
- Inter-annual and/or sub-seasonal ***temporal resolution*** might be needed in some cases; requires detailed, regional study (e.g., Amazon)

Val Martin et al., Remt. Sens. 2018

Global Distribution of Percent Injected Within/Above the PBL

Based on MERRA-2 Hourly PBL 10:00-13:00 LT



Accounting for uncertainty
FT = PBL + 500 m

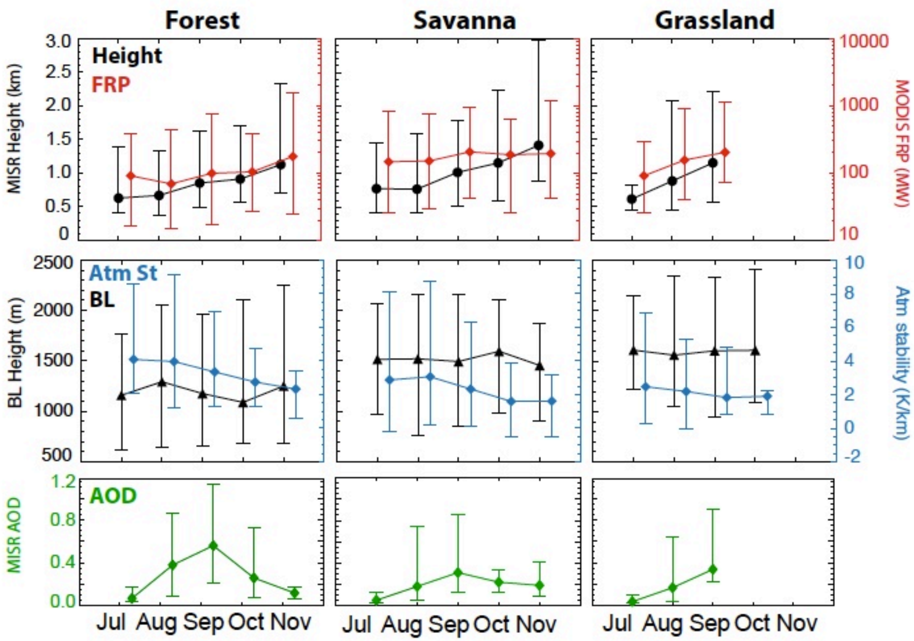
[PBL from MERRA-2}

2 km threshold avoids dependence on PBL height estimate

Val Martin et al., Remt. Sens. 2018

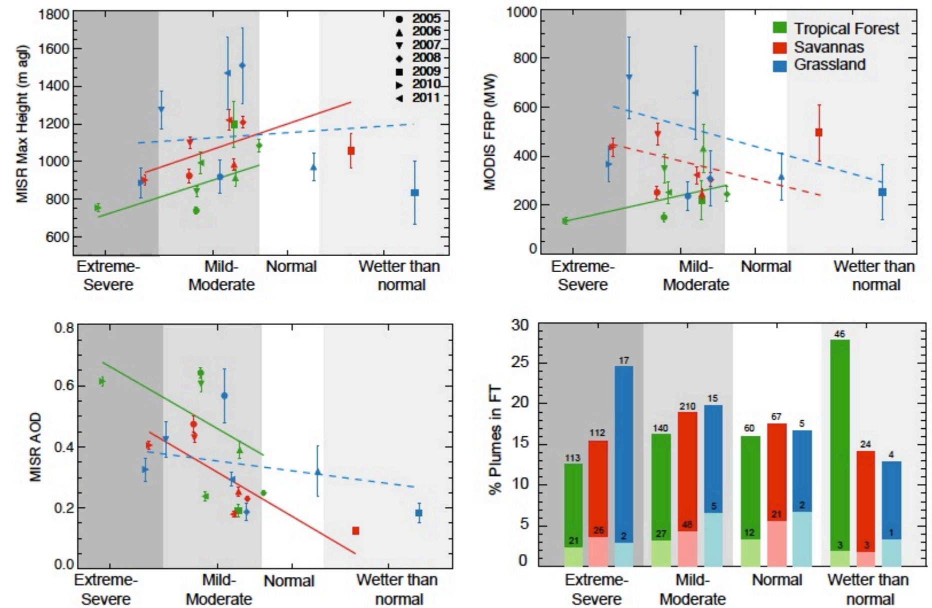
Amazon Plume-Height Climatology

2005-2012



Seasonal Cycle of 5 parameters, stratified by ***Vegetation Type***

MISR Plume Height, MODIS FRP, Model BL Height & Atm. Stability MISR AOD



Interannual patterns of 4 parameters, stratified by ***Drought Index***

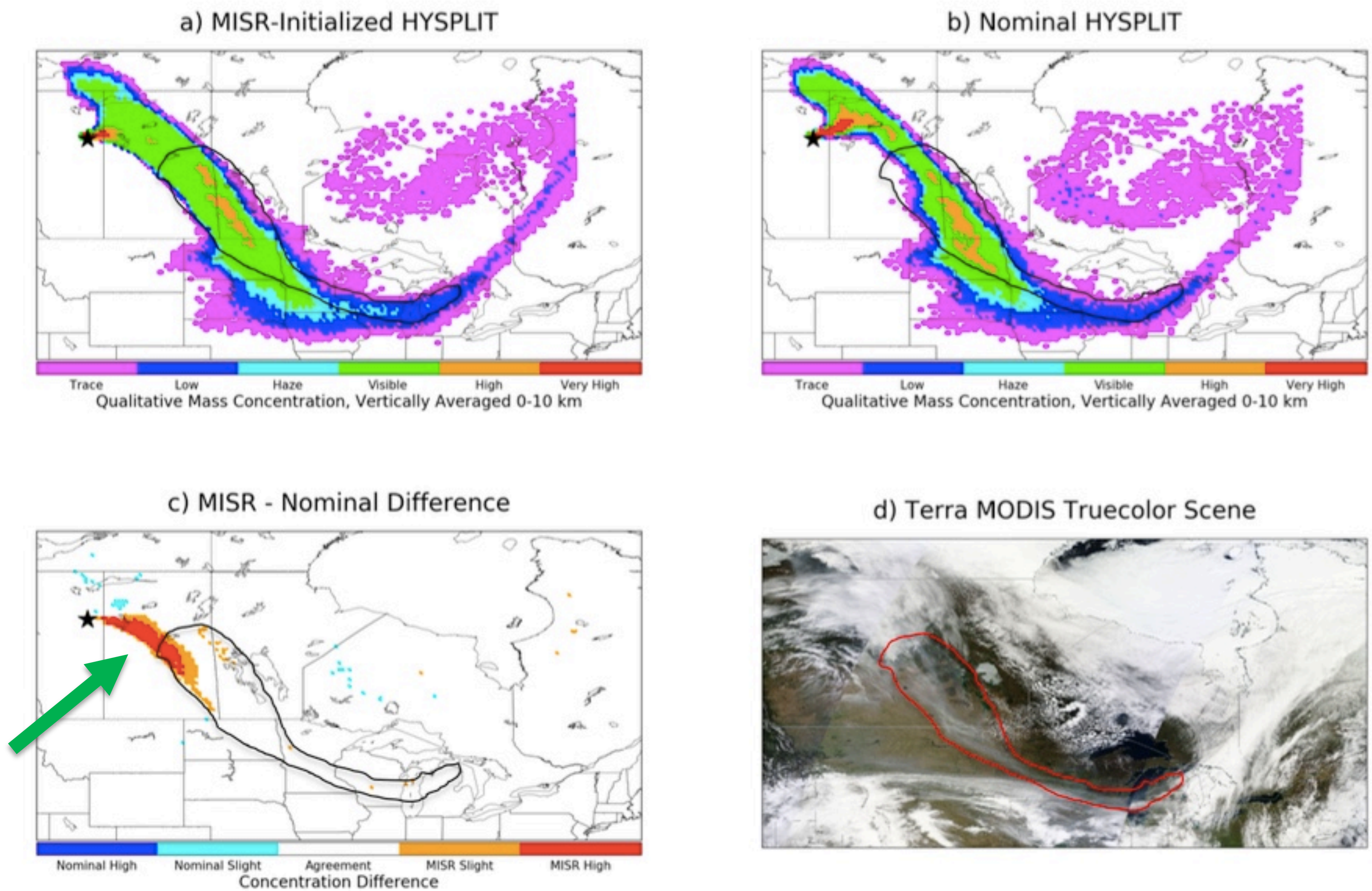
MISR Plume Height, MODIS FRP, MISR AOD, % in Free Troposphere

- ***FRP*** **and** ***Height*** **tend to** ***increase*** **as the fire season progresses, for all major Amazon biomes**
- ***AOD*** **tends to** ***increase***, ***Height*** **tends to** ***decrease*** **for forest & savannah in drought years**

Gonzalez-Alonso et al., ACPD 2018

Ft. McMurray Wildfire, Alberta Canada

May 07, 2016 (Day 2) NOAA HySPLIT Model



When the injection height is above the PBL in regions with significant wind shear, MINX-initiated simulations better represent satellite observations.

Vernon et al., AMT 2018

Why We Care About *Aerosol Air Mass Type*

Some applications of satellite-mapped aerosol type, especially when ***combined with*** otherwise-constrained, detailed particle properties:

- ***Source Attribution***

- Mapping 3-D ***Aerosol Absorption*** that mediates impacts on ***atmospheric stability structure*** and can affect ***convection***, ***cloud evolution***, and ***larger-scale atmospheric circulation***

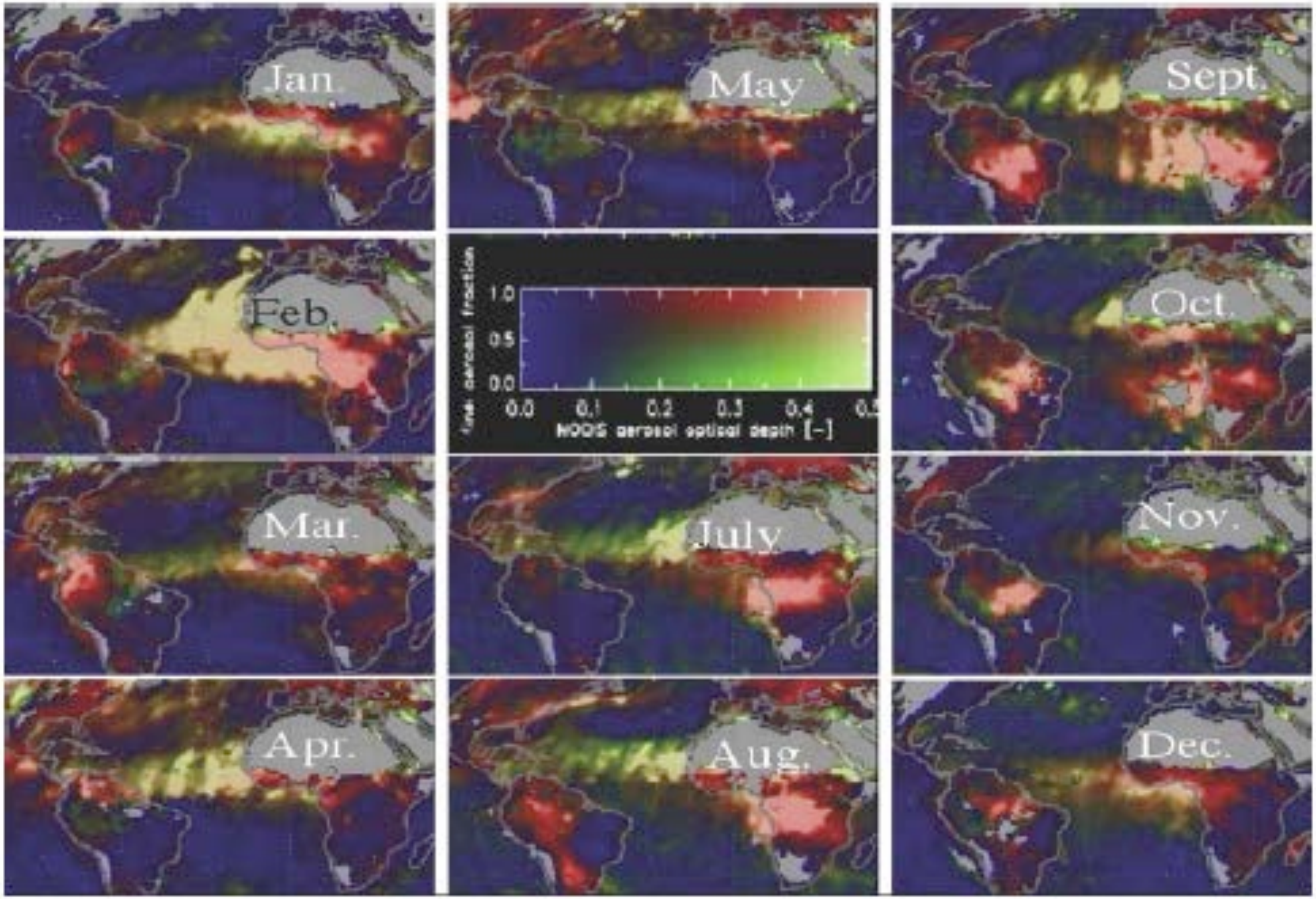
- Mapping ***Particle Hygroscopicity*** required to account for humidity-dependent ***particle optical property changes*** as well as ***particle activation conditions*** that initiate cloud formation

- Deducing ***Mass Extinction Efficiency*** (MEE) distributions, required to ***constrain & validate air quality***, ***aerosol-transport***, and ***climate model*** aerosol mass with remote-sensing-derived particle ***optical*** properties.

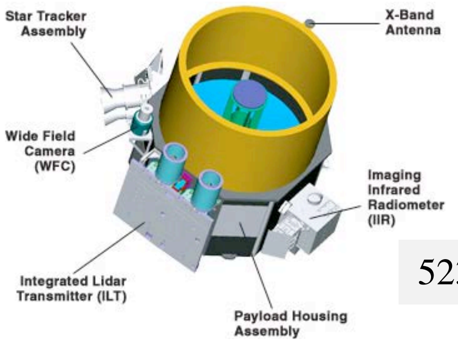
Aerosol Air Mass Type derived from remote sensing can provide ***2-D and 3-D mapping required*** for many of these applications.

One MODIS Aerosol Type Classification:

Low AOT (blue), High AOT+Coarse (green), High AOT+Fine (red)



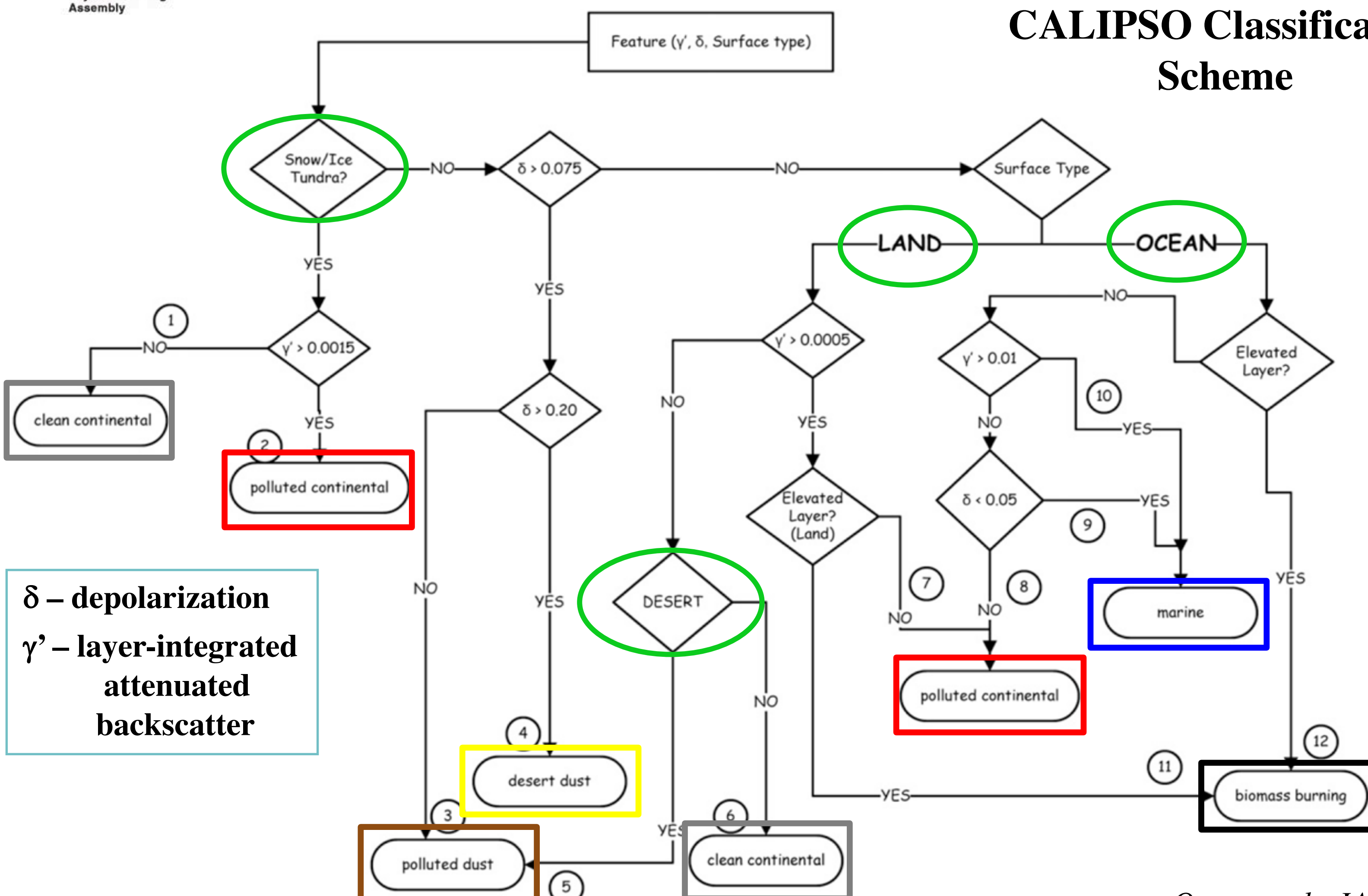
Kaufman et al., JGR, 2005



CALIPSO 6-Type Interpretive Aerosol Classification Scheme

523 and 1064 nm channels; ~100m horizontal resolution

CALIPSO Classification Scheme

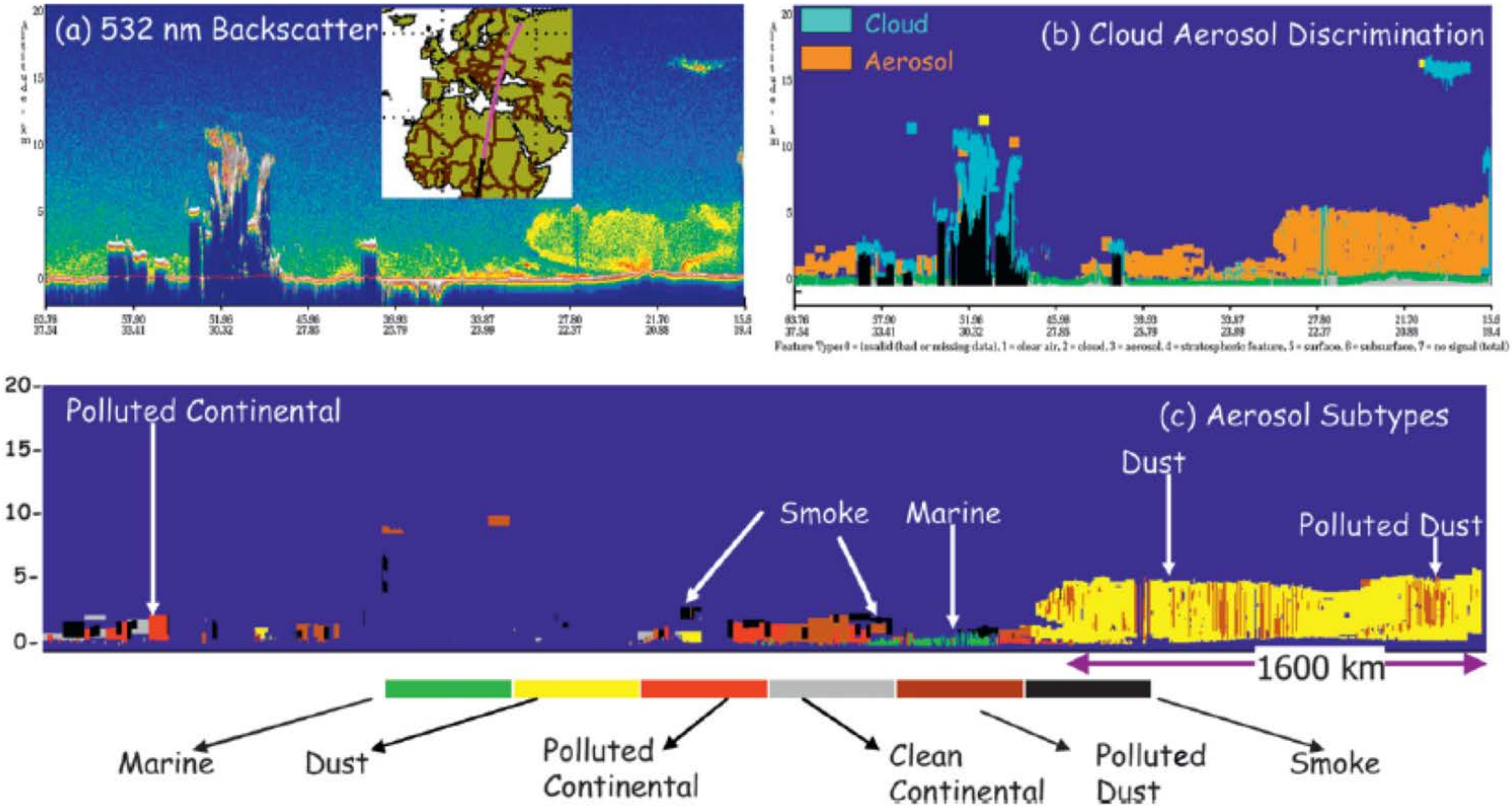


δ – depolarization

γ' – layer-integrated attenuated backscatter

Omar et al., JAOT 2009

CALIPSO 6-Grouping Aerosol Type Classification

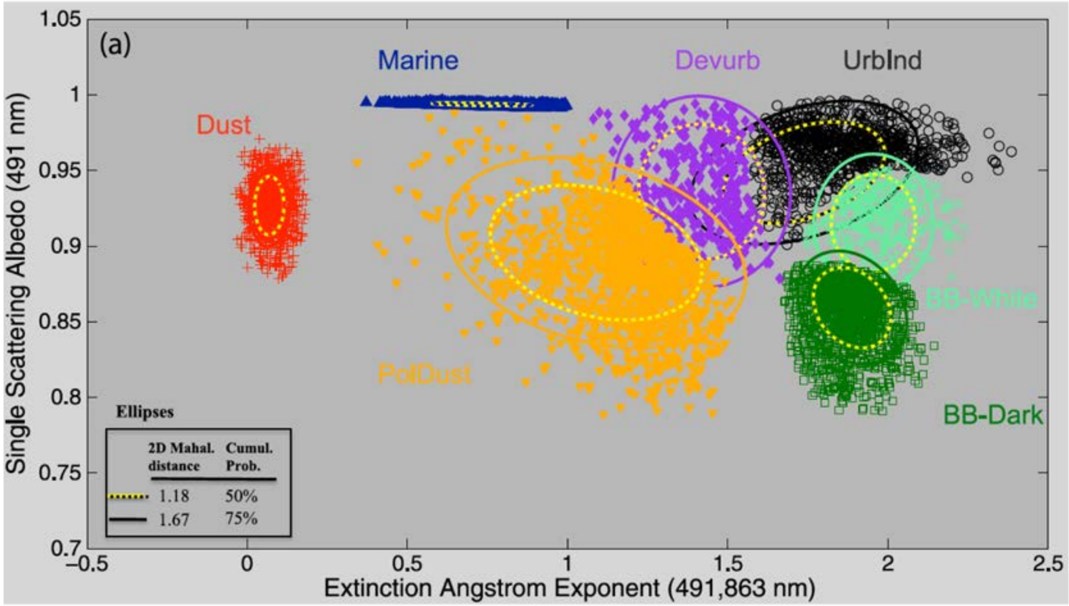


Omar et al., JAOT 2009

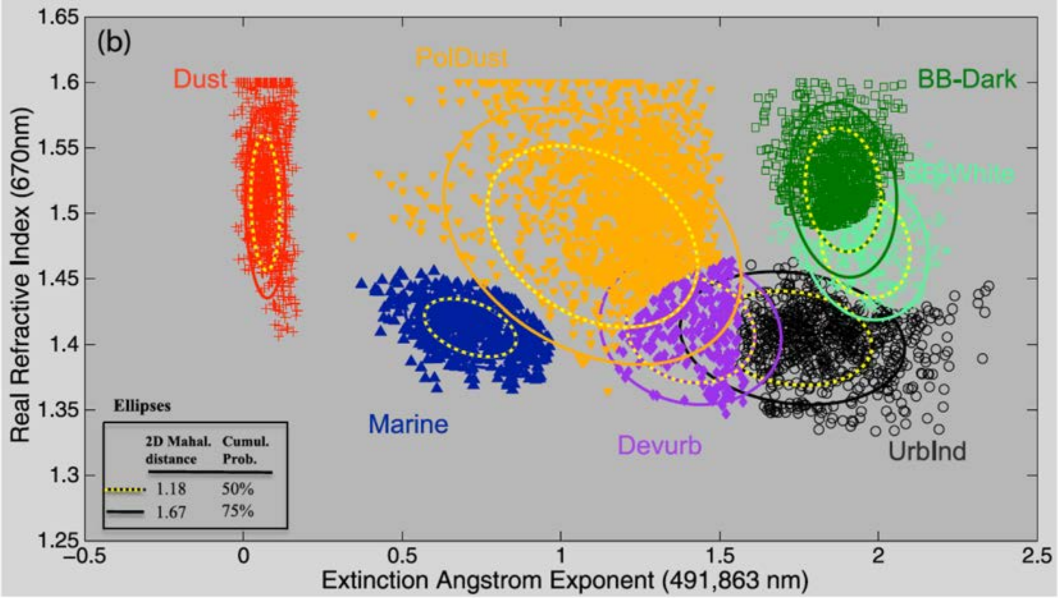
AERONET Aerosol Type 7-Grouping Classification

Four-parameter AERONET-derived classification:

- $EAE_{491,863}$
- SSA_{491}
- RRI_{670}
- $dSSA_{863-491}$



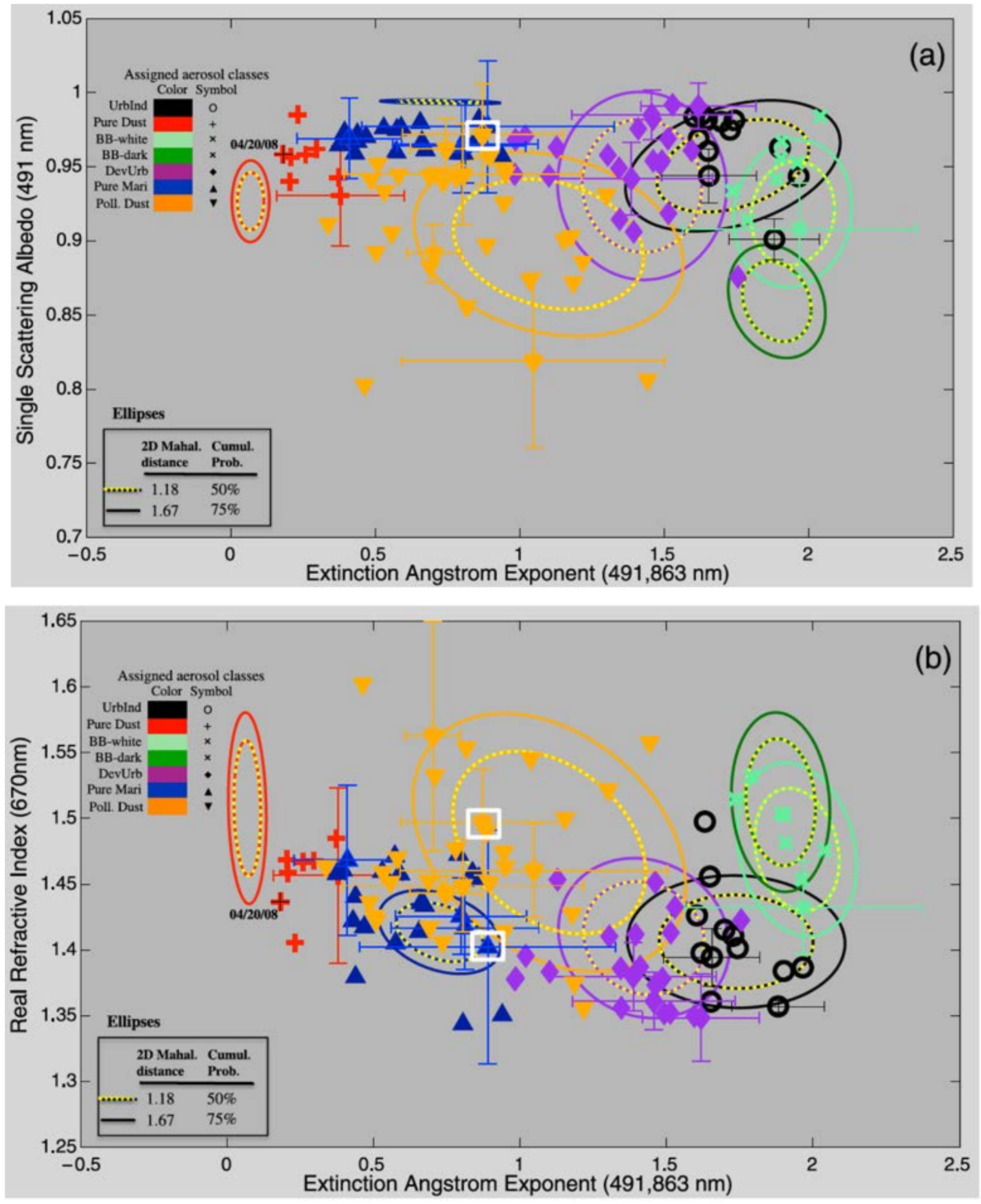
7 Groupings SSA_{491} vs. Extinction ANG



7 Groupings Real RI_{670} vs. Extinction ANG

Russell et al. JGR 2014

PARASOL data at Forth Crete projected onto the AERONET Aerosol Type Classification



Four-parameter AERONET-derived classification:

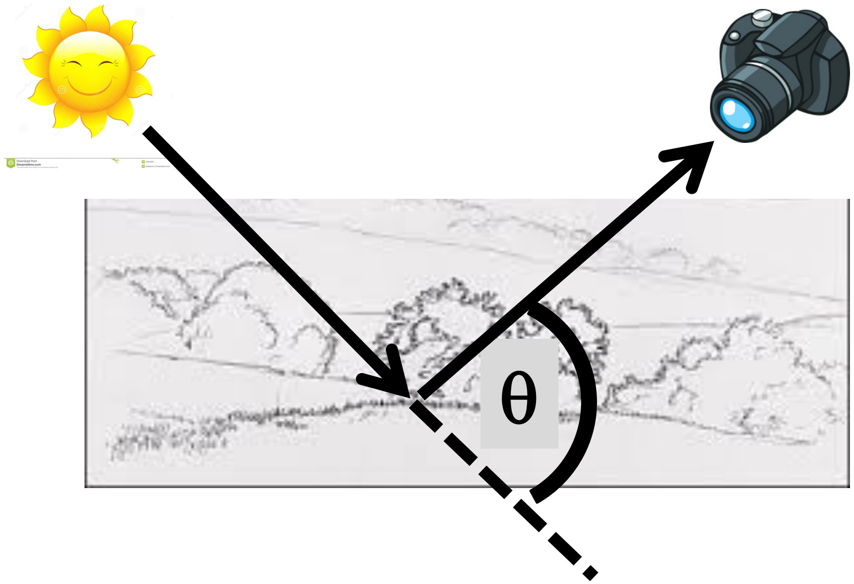
- $EAE_{491,863}$
- SSA_{491}
- RRI_{670}
- $dSSA_{863-491}$

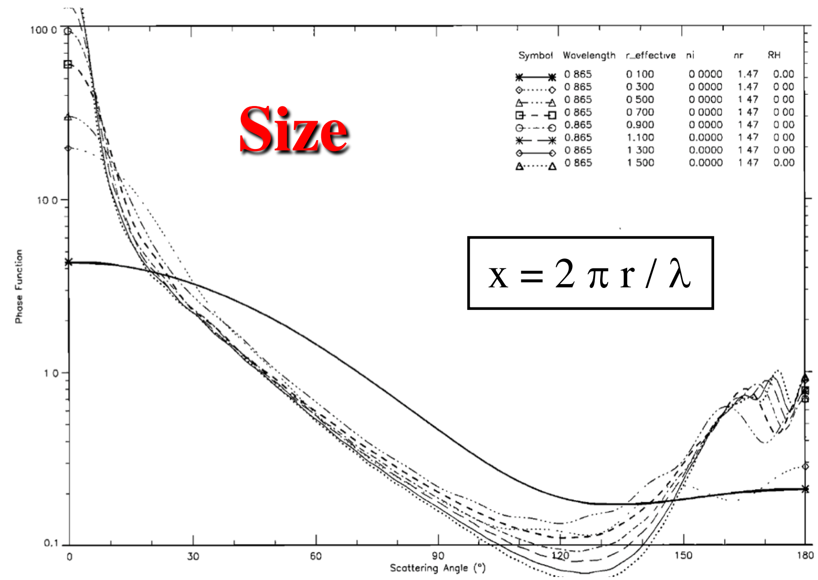
7 Groupings SSA_{491} vs. Extinction ANG

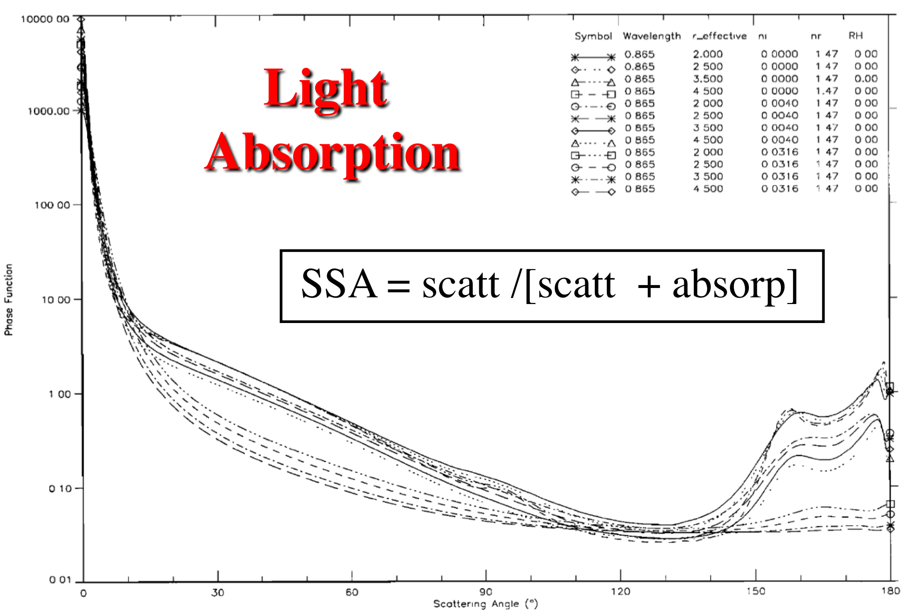
7 Groupings Real RI_{670} vs. Extinction ANG

Russell et al. JGR 2014

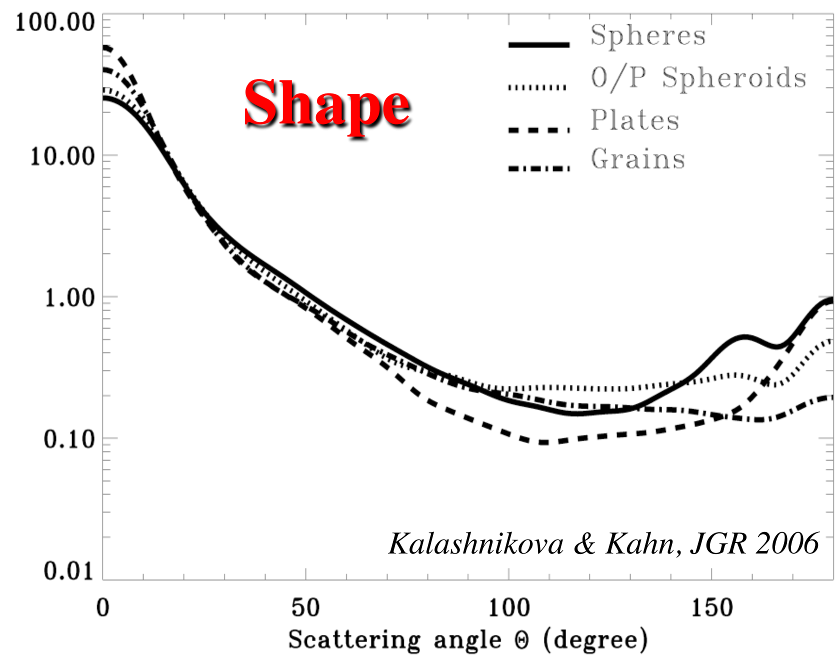
Single-scattering Phase Functions for **Different Particle Properties**





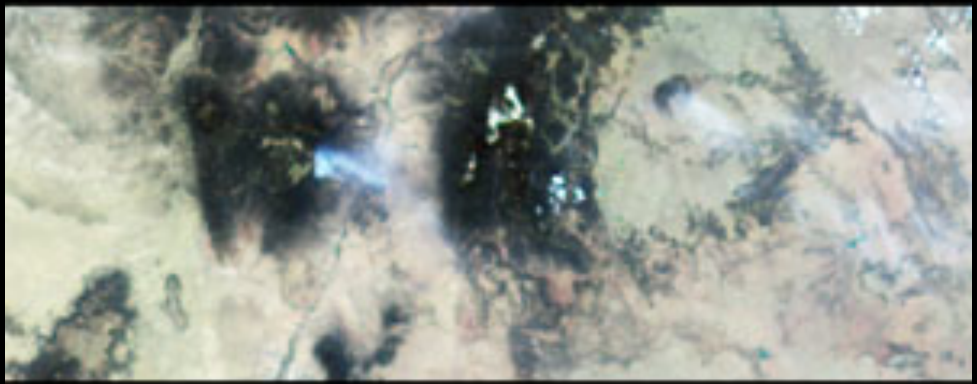


Kahn et al., JGR 1998



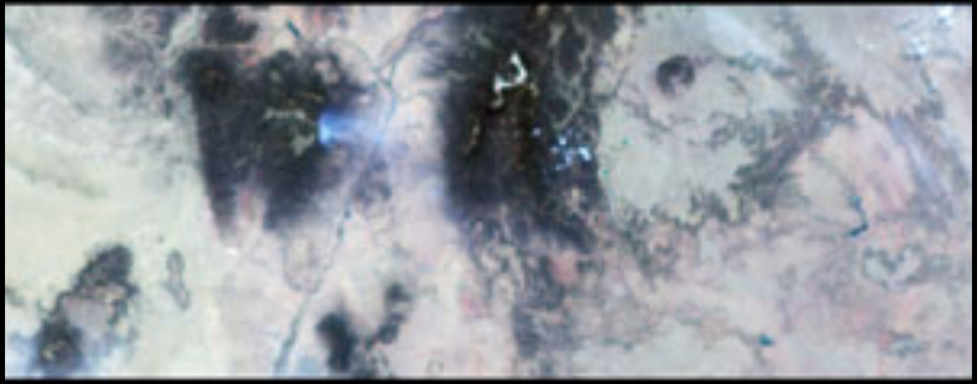
Kalashnikova & Kahn, JGR 2006

Los Alamos Fire, New Mexico May 9, 2000



MISR 60˚ Forward

MISR Nadir

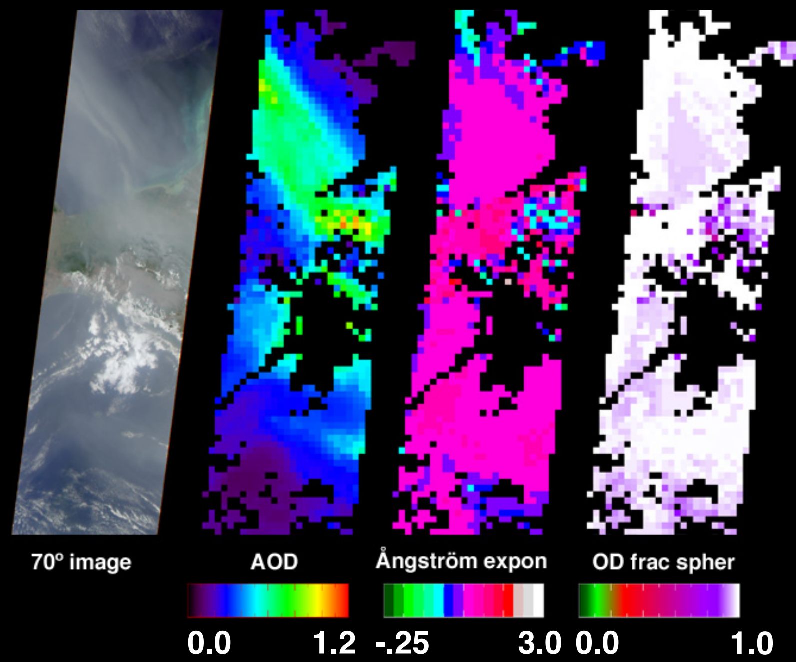


MISR 60˚ Aft

Smoke from Mexico -- 02 May 2002

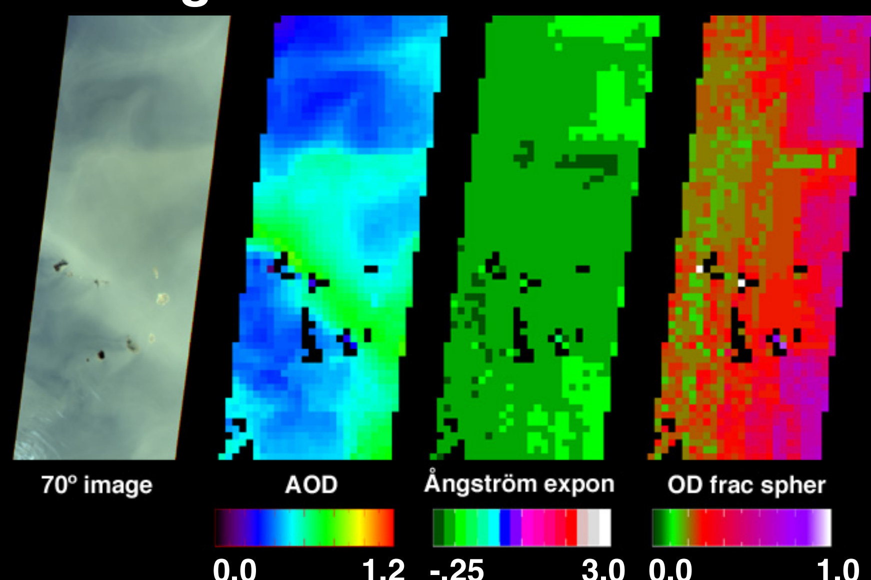
MISR Aerosol Type:

- Size
- Shape
- Brightness



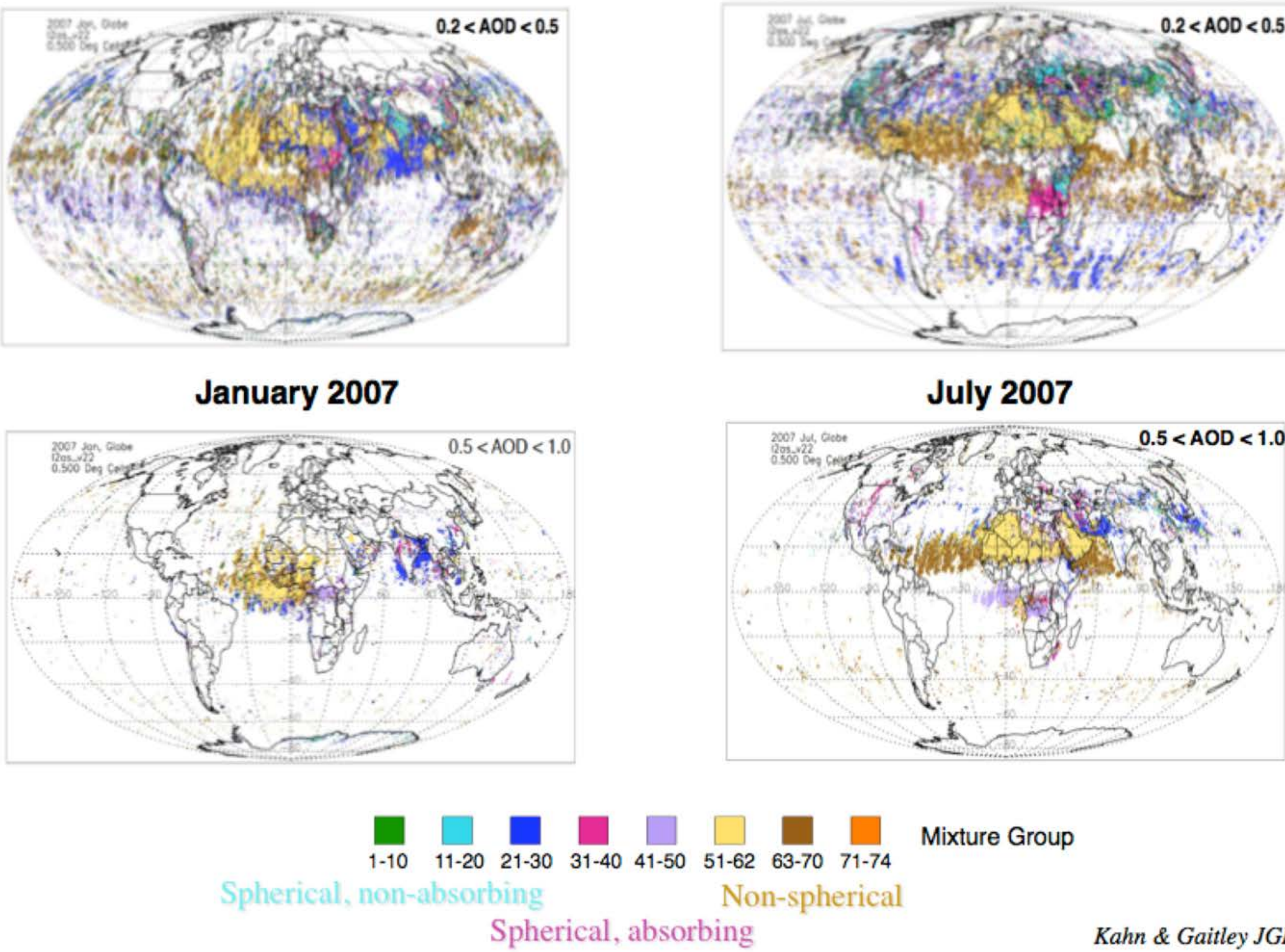
Medium Spherical Smoke Particles

Dust blowing off the Sahara Desert -- 6 February 2004



Large Non-Spherical Dust Particles

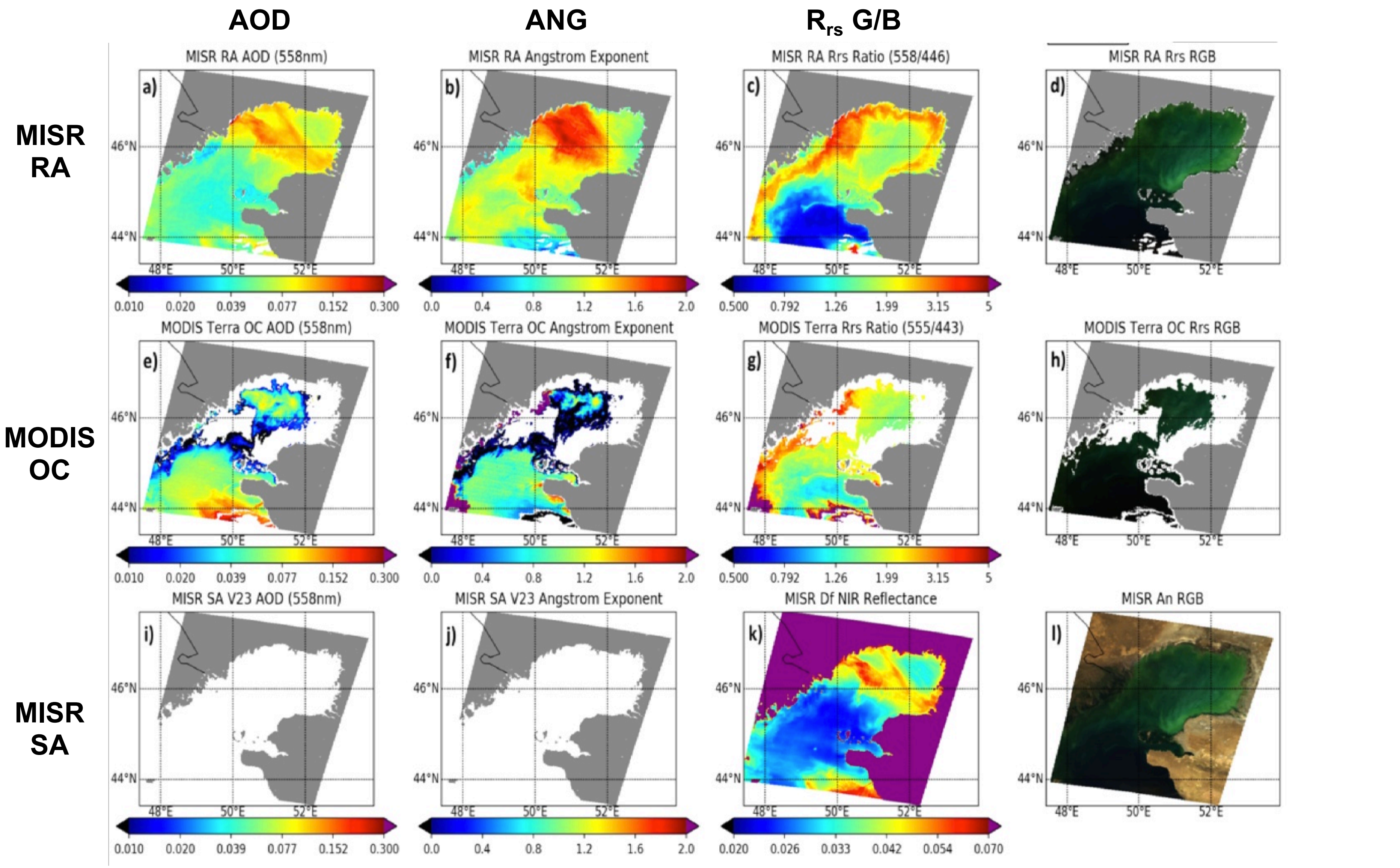
MISR Aerosol Type Discrimination



Kahn & Gaitley JGR 2015

MISR *Research* Retrievals Over *Shallow, Turbid, & Eutrophic* Water

Bay of Bengal 01/29/2015 (*Turbid*)

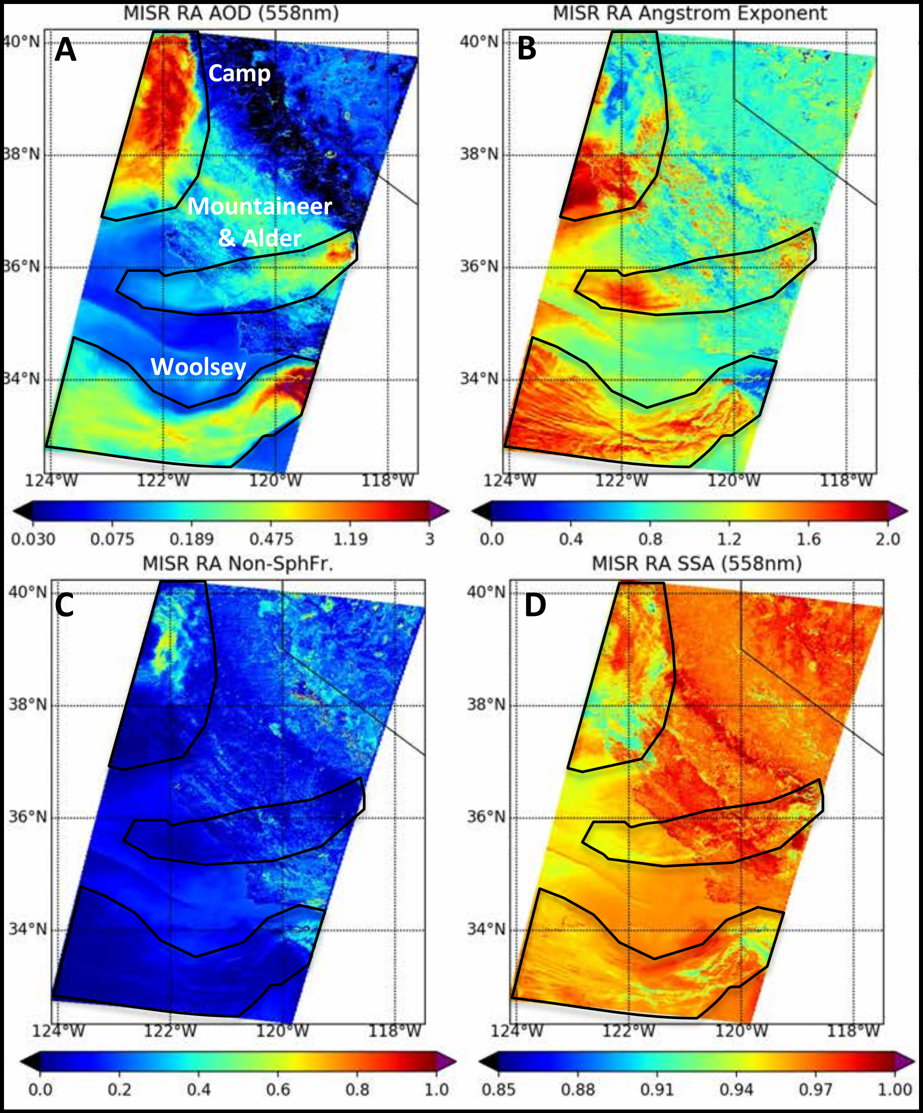


Limbacher & Kahn, AMT 2018

California fire plumes – *Smoke Particle Properties*

MISR Active Aerosol Plume-Height (AAP) Project *9 November 2018*

MISR Research Algorithm (RA) – Aerosol Amount and Type Retrievals



The MISR Research Aerosol (RA) retrieval algorithm produces (A) aerosol amount (optical depth – AOD), (B) an aerosol size constraint (Angstrom Exponent) (C) fraction of non-spherical particles, and (D) particle light-absorption (SSA).

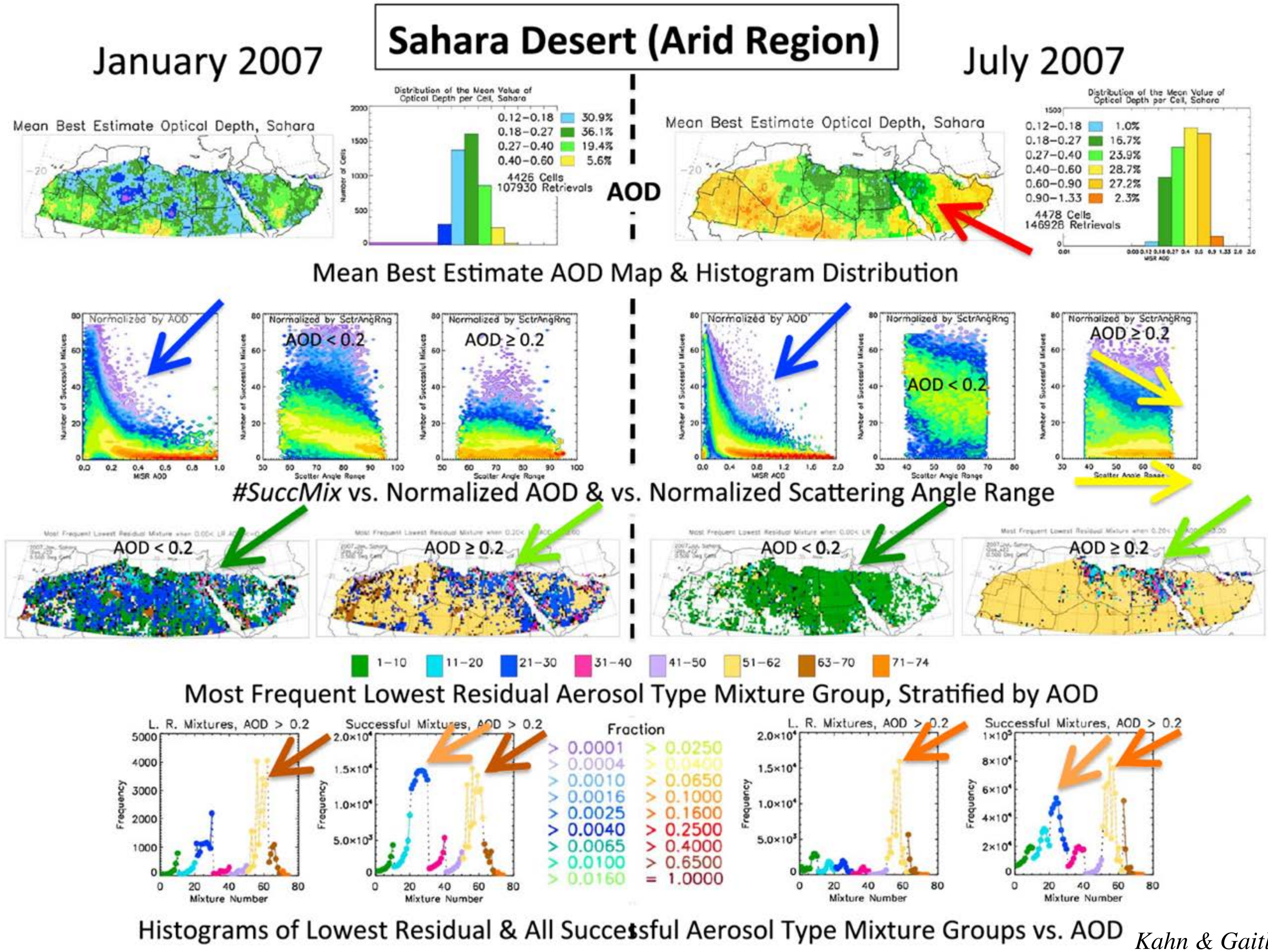
Near the Camp fire *source region* the particles tend to be *large* (low Angstrom Exponent) and *non-spherical particles*, probably from burning in the town of Paradise. Aerosols are smaller and more spherical downwind, probably as the plume mixes with *smoke from burning forest*.

The Alder and Mountaineers plume-height analysis, which relies on pixel-level contrast elements in the imagery, tracked the plume for only 50 km. However, the MISR RA, more sensitive to thin aerosol layers, observes the plume *extending to the Pacific ocean*. This result highlights the *possible influence of plumes* even when *particle concentrations render them sub-visible*.

The southernmost Woolsey fire displays similarities to the Camp fire with *near source regions containing larger particles*. This area also contained a significant fraction *of non-spherical particles (~40%)*, though at a *lower concentration than the Camp fire (70%)*. The shift in particles from large, non-spherical to small, spherical characteristics suggests that the bigger particles are settling to the surface, and it corresponds to the decrease in plume altitude.

V. Flower, R. Kahn, J. Limbacher / NASA GSFC

MISR Aerosol Type Discrimination



Kahn & Gaitley JGR 2015

MISR Aerosol *Quality Statement*

ATMOSPHERIC SCIENCE DATA CENTER

MISR Level 2 Aerosol/Surface Products Quality Statement July 01, 2014

Quality Designations:

- **Stage 3 Validated:** AEROSOL - aerosol optical depth over heterogeneous surfaces and dark water. LAND - HDRF, DHR, BHR
- **Stage 2 Validated:** AEROSOL - aerosol Angstrom exponent, aerosol single-scattering albedo, AOD due to small, medium, large, spherical, non-spherical particles; LAND - NDVI, LAI and FPAR (excluding needleleaf forest), MRPV (BRFModParam), BHRPAR, DHRPAR

1. MISR Level 2 Aerosol Product (a.k.a. AS_AEROSOL, MIL2ASAE)

[This product is generated by the MISR PGE9 executable code]

The MISR Aerosol Product is reported over 17.6 km regions, using data from up to 36 channels in a 16 x 16 array of 1.1 km radiance pixels. Algorithm pre-processing executes a range of data-screening operations, and provided a minimum number of pixels pass all the tests, an aerosol retrieval is performed [*Martonchik et al.*, 2009; *Kahn et al.*, 2009a]. Different retrieval approaches are used over land and water, as discussed in the references cited. Detailed validation of MISR-retrieved aerosol optical depth has been performed, and aerosol microphysical property validation is underway, as described below.

1.1 MISR Aerosol Product Maturity

Status	Parameter
Stage 3 Validated	RegBestEstimateSpectralOptDepth, RegMeanSpectralOptDepth
Stage 2 Validated	Reg*AngstromExponent, Reg*SpectralSSA, Reg*SpectralOptDepthFraction

Product users should be aware that the aerosol optical models used in the retrieval analyses provide a practical means of deriving optical depth, and ***optical depth has been validated***, as described below. However, it is more difficult to obtain reliable ground truth data to compare with MISR total column aerosol type (particle microphysical property) retrievals; ***validation of retrieved particle microphysical properties is continuing***, using a combination of AERONET sun photometer [e.g., *Kahn et al.*, 2010] and detailed field campaign data [*e.g., Kahn et al.*, 2009b]. As the MISR retrieval process matures, the aerosol component and mixture optical models will be refined, and the thresholds used in the algorithm acceptance criteria will be further reduced, yielding more tightly constrained results.

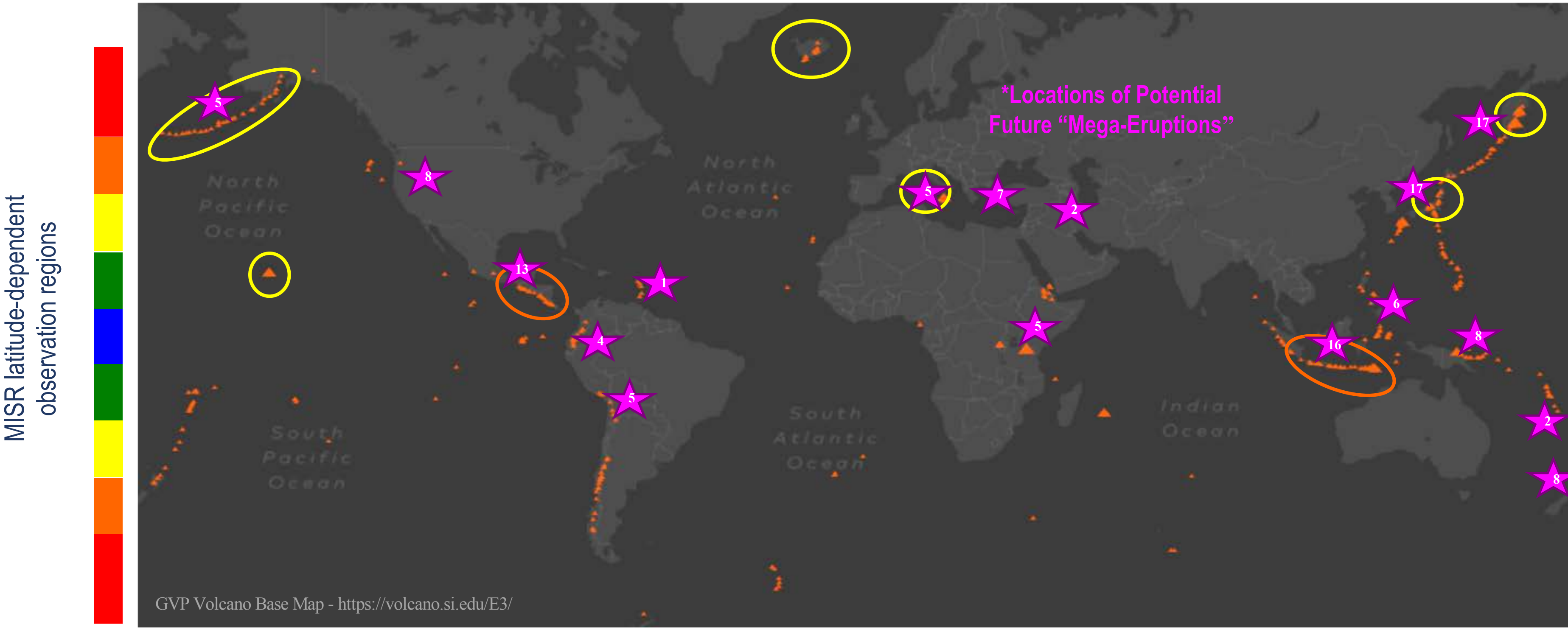
Satellite Aerosol-Type Summary

- Remote-sensing can provide optical constraints interpreted as particle ***Size, Shape, and Indices of Refraction***
- A ***further*** interpretative step, entailing additional assumptions, reports particle ***Chemical Composition***
- Remote-sensing ***sensitivity to particle properties is much more dependent than AOD on retrieval conditions***
- Improvements in ***Calibration, Surface Representation, Particle Microphysical Properties*** needed to make progress
- ***Validation Data*** for aerosol type are very limited

  -- ***Model simulations*** and ***In Situ measurements*** can help

- ***In situ Data*** also needed for particle microphysical properties ***unobtainable from remote-sensing***

Volcanology from Space



MISR latitude-dependent observations/month

- ~15
- ~11
- ~9
- ~6
- ~4

Suborbital Monitoring Networks

- Well-monitored
- Partially-monitored

Global Active Volcanism (1960-2017)

- VEI 0
- VEI 1
- VEI 2
- VEI 3
- VEI 4

***VEI – Volcanic Explosivity Index**

Key Information from Global Volcano Monitoring

Aviation and downwind environmental ***hazard response***

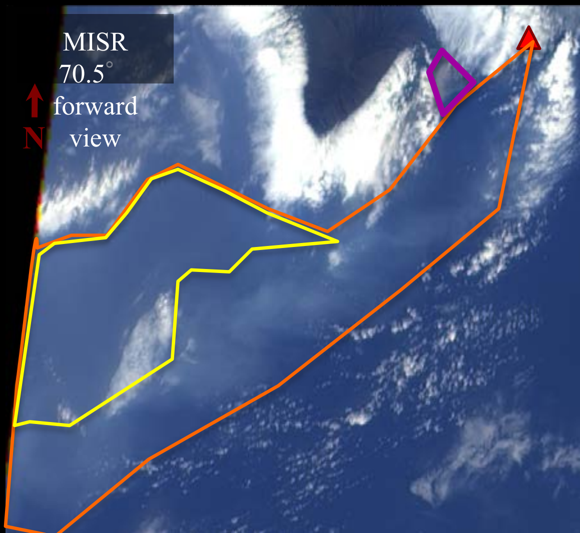
Constraints on ***air quality and climate modeling***

Surface and subsurface ***geology implications***

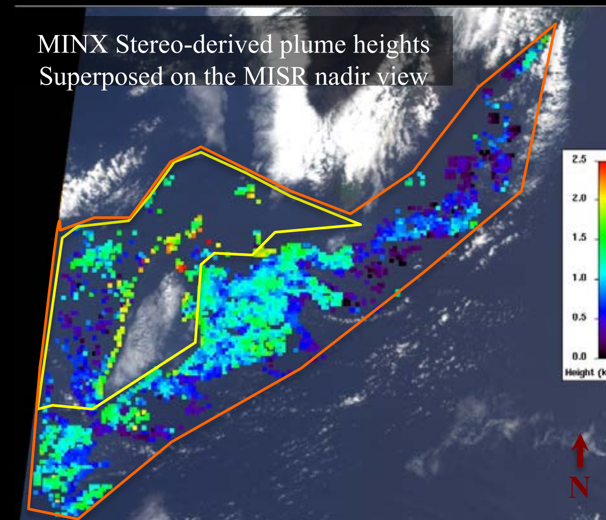
Flower & Kahn 2017-2019

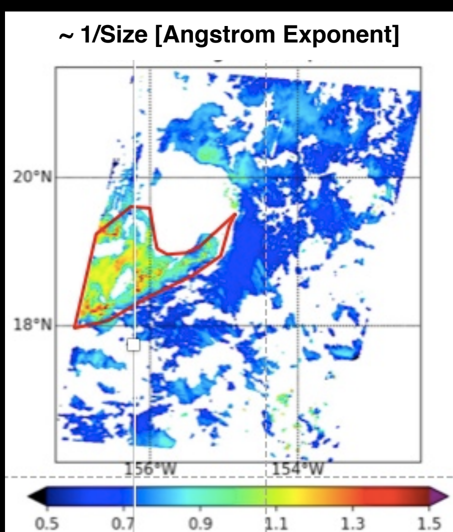
Volcanic eruption plume from *Kilauea Volcano*, Hawaii

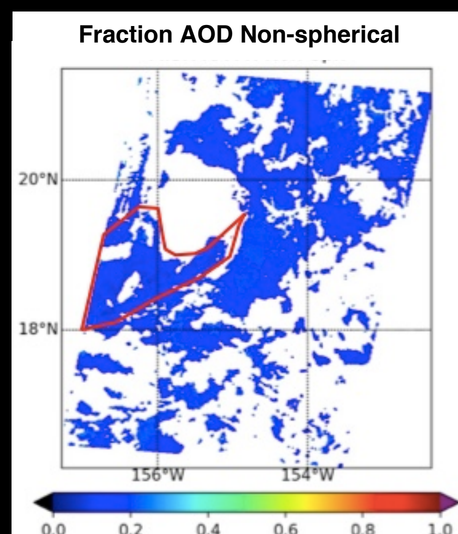
MISR Active Aerosol Plume-Height (AAP) Project 22 May 2018

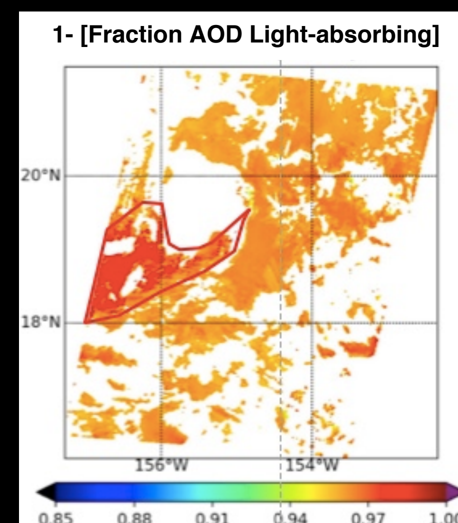


The *core* and ***diffuse*** plumes concentrate at ~1±0.5 km above the *ocean*, dispersing to the west. A ***small summit plume*** is elevated ~1 km above the *terrain*.





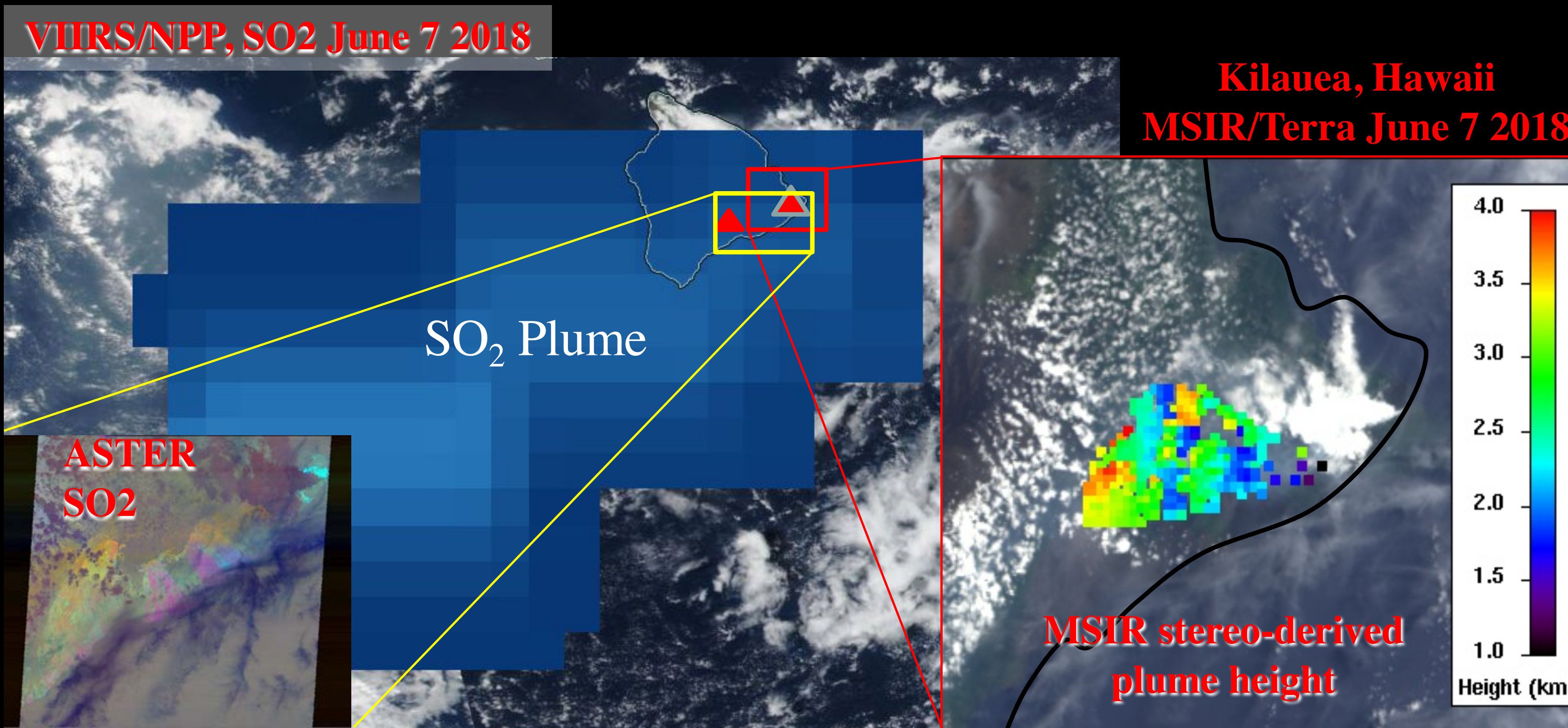




The particles are spherical, smaller and brighter than background – sulfate, not ash dominated.

V. Flower, R. Kahn, J. Limbacher/ NASA GSFC

SO_2 Concentration + *Sulfate Plume-height* maps = ***Sulfur Emission Rate***: "VOG" (Volcanic Fog)

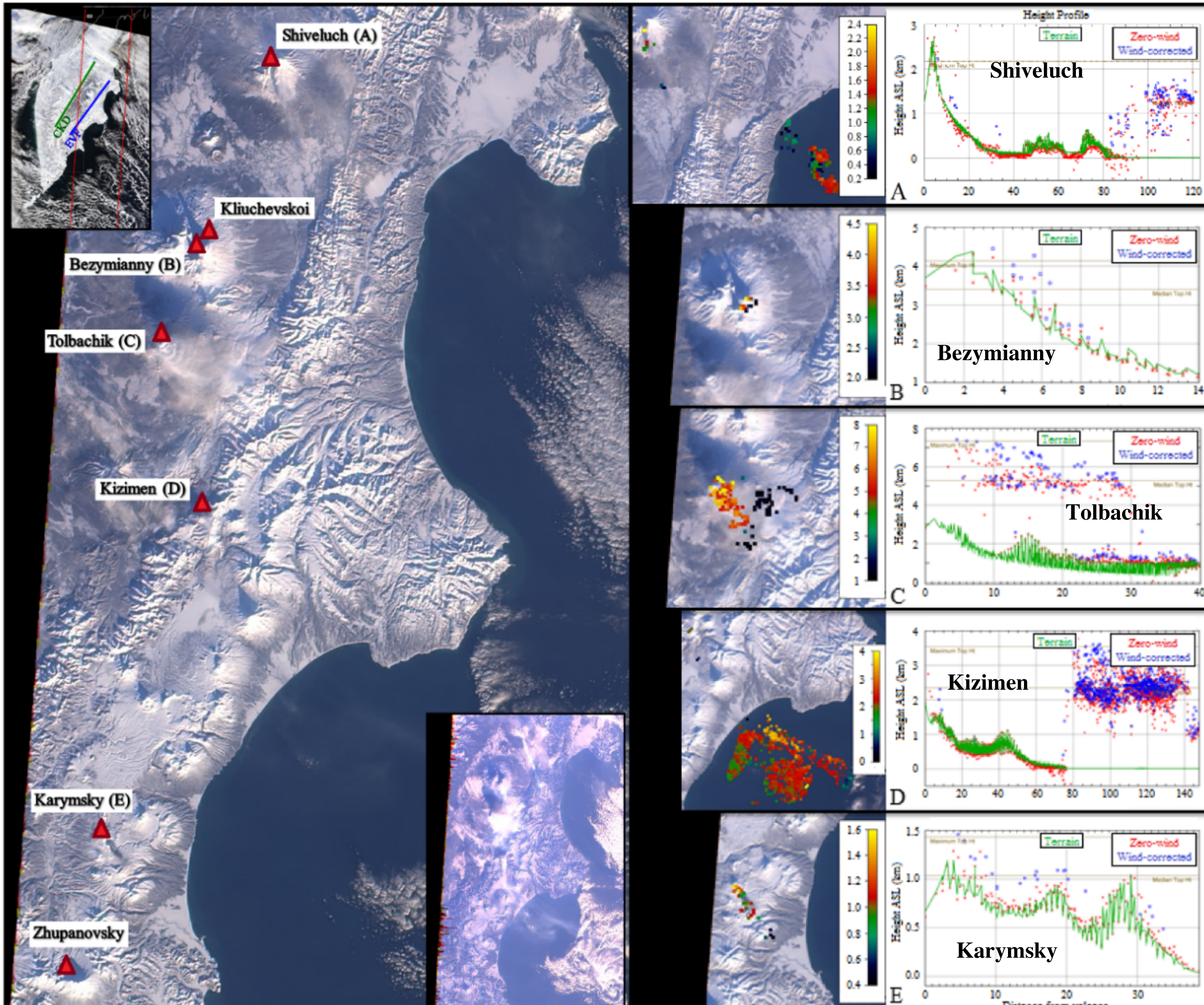


- ***OMI UV and ASTER Infrared*** estimate sulfur dioxide (SO_2) concentrations + ***MISR Plume Height = Sulfur Emission Rate,*** a possible ***air quality hazard***.

Five *Kamchatka Volcano Plumes* *06 January 2013*

CKD: Central Kamchatka Depression
(Higher volitiles: subducting Emperor Sea Mount)

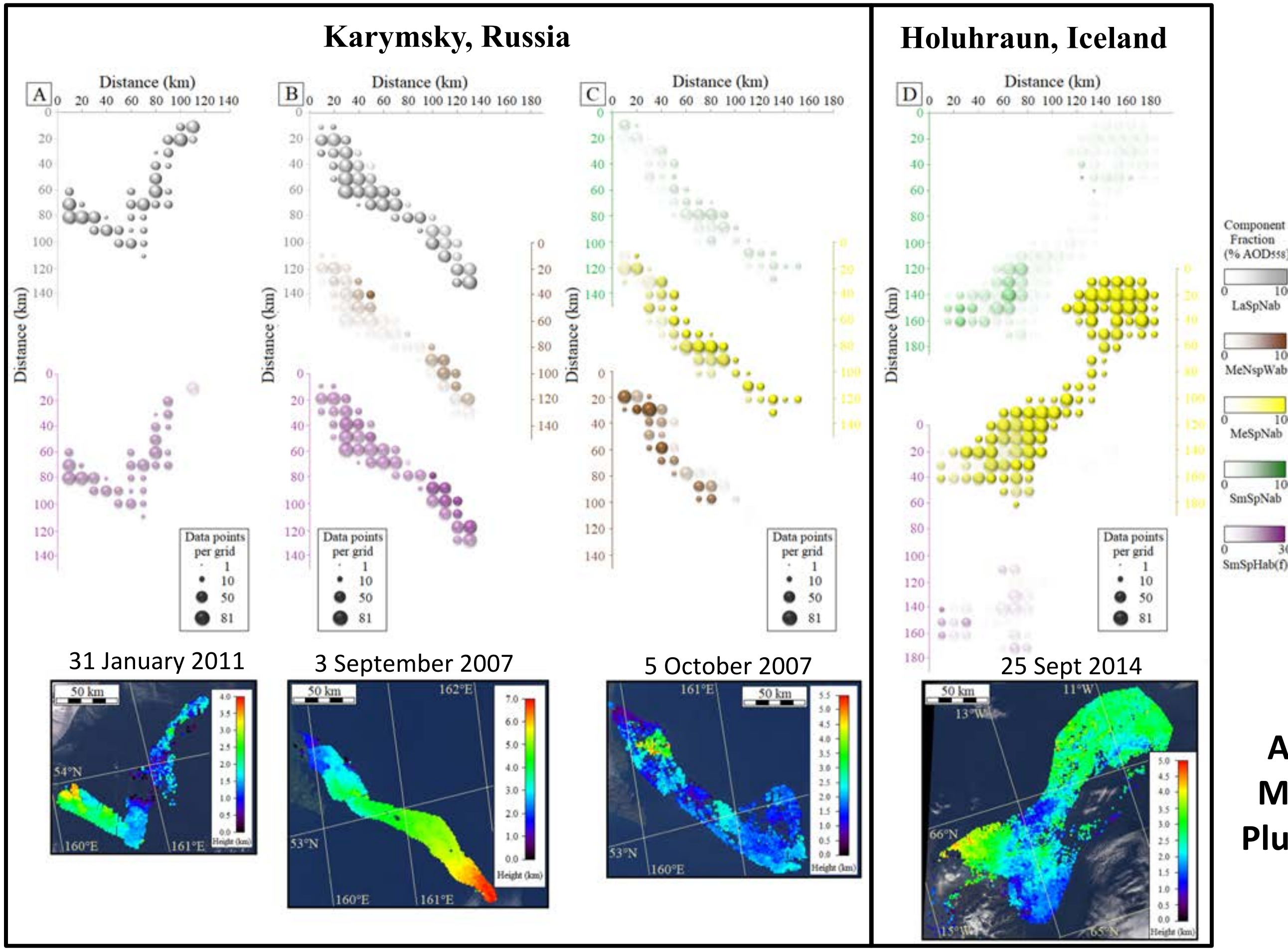
EVF: Eastern Volcanic Front
(Lower volitiles: subducting Pacific Plate)



Flower & Kahn J. Volc., 2017a

MISR *Research* Aerosol Retrieval Algorithm Particle Types

[Constraints on particle size, shape, light-absorption properties]



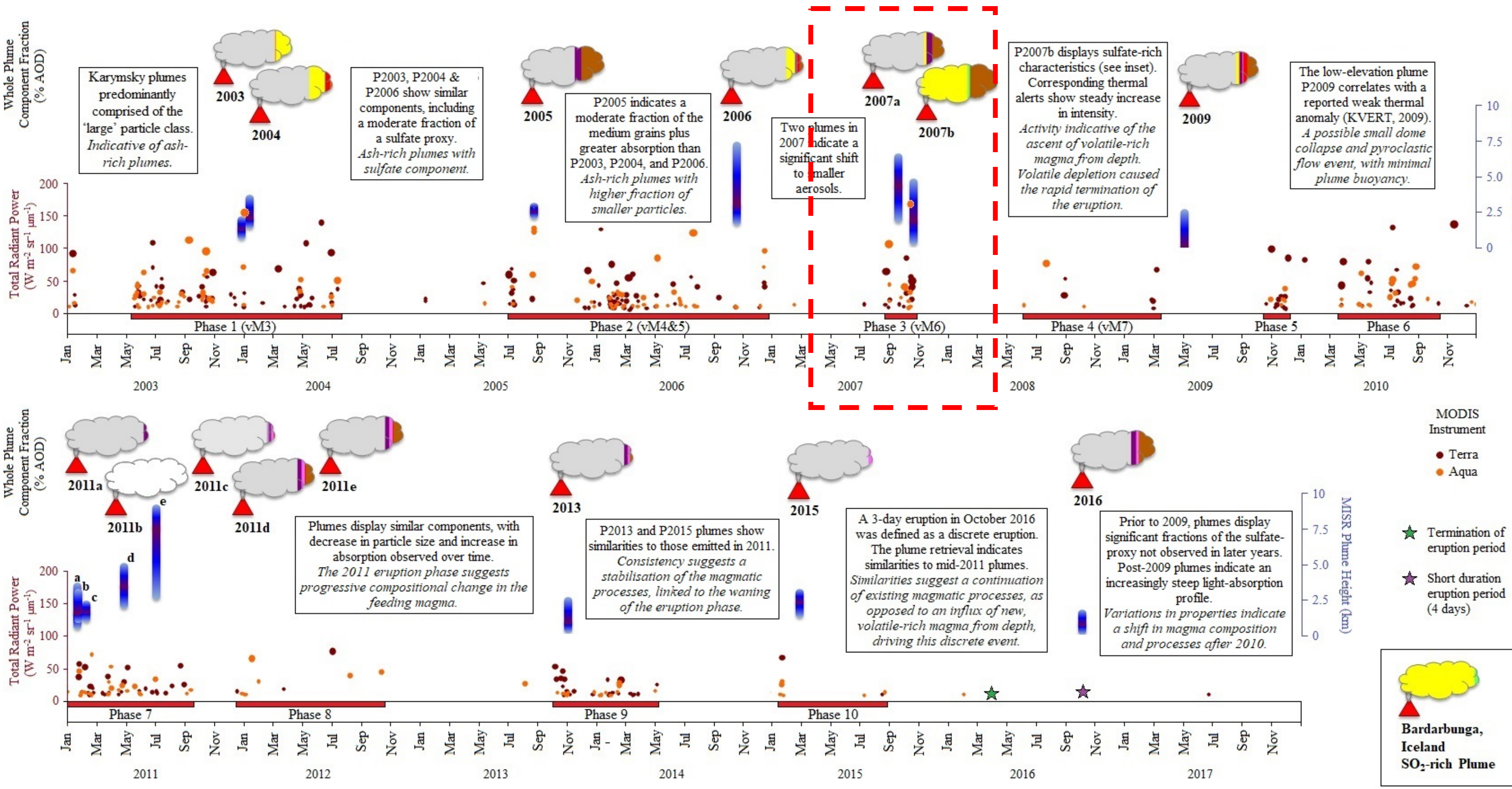
Associated MISR stereo Plume heights

Particle-property maps reflect *plume-to-plume (magma) differences* & *downwind particle evolution*

Grey=ash-proxy; Purple, Brown=light-absorbing; Green=spherical non-absorbing; Yellow=sulfate-proxy

Flower & Kahn ACP., 2018

Volcanology from Space

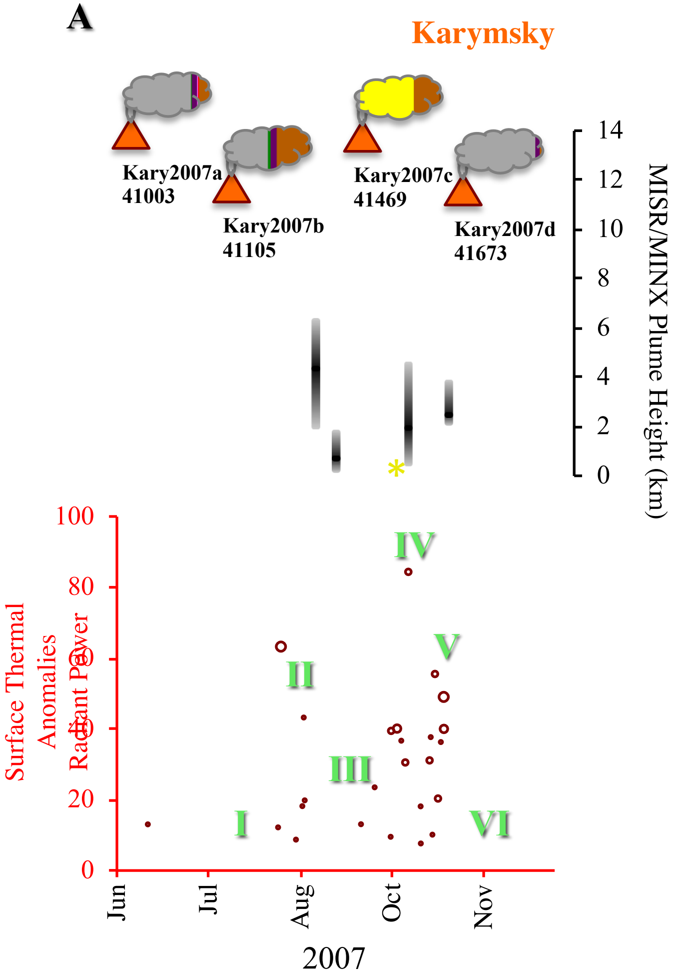


SmSpNab	Small (~0.06 μm), spherical, non-absorbing
MdSpNab	Medium (~0.57 μm), spherical, non-absorbing
LaSpNab	Large (~1.28 μm), spherical, non-absorbing
SmSpHab(f)	Small (~0.12 μm), spherical, highly absorbing ('flat' absorption profile)
SmSpHab(s)	Small (~0.12 μm), spherical, highly absorbing ('steep' absorption profile)
SmSpMab(f)	Small (~0.12 μm), spherical, moderately absorbing ('flat' absorption profile)
MdNspWab	Medium (~0.75 μm), weakly-absorbing dust grains
LaSpdWab	Large (~2.4 μm), weakly-absorbing coarse dust spheriods

Flower & Kahn, 2017c

Karymsky Volcano 2007 Eruptions – Geological Interpretation

A



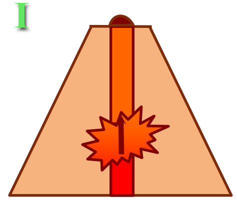
MISR Research Aerosol Retrieval (RA)

- Ash Particles
- Fine ash particles
- Spherical absorbing components
- Spherical non-absorbing components

* OMI SO_2 observation – 670t

B

I

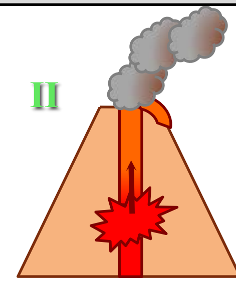


System is ***capped preventing lava flow*** development.

Minimizing the ***number and size*** of ***plumes***.

System put under ***strain*** by ***upwelling magma*** from depth.

II

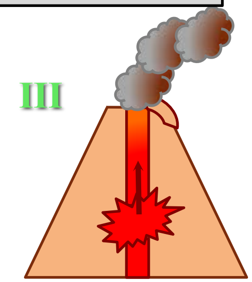


Pressure of upwelling magma ***overcomes cap*** causing ***explosive decompression*** of the system.

Fragmentation of the ***shallow, volatile poor magma*** generates ***ash rich plumes*** with ***large particles.***

Concurrent ***outflow of lava*** correspond to thermal anomaly detection.

III

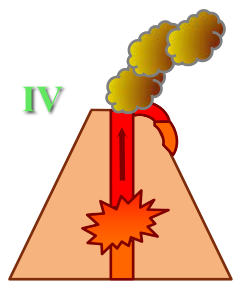


Influx of ***fresh magma*** combined with ***shallow, volatile poor magma***.

Generates ***ash rich plumes***, with ***smaller particle size.***

No thermal anomaly detection suggesting ***no surface lava flows***

IV

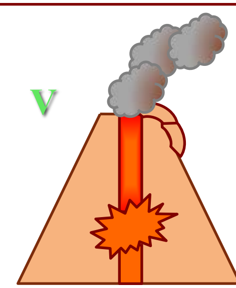


Decompression of the system draws ***volatile rich magma from depth***.

Generation of ***plumes*** with ***small ash particles*** and a ***higher fraction*** of ***sulfate and water***.

Lava flow extension corresponds to an increase in thermal anomalies.

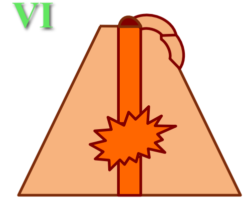
V



Decreasing influx of the ***volatile rich magma from depth*** corresponds to a shift back to ***ash rich plumes*** with minimal volatile components.

No thermal anomaly detection indicates ***cessation of lava flow extension.***

VI



Reduction in ***upwelling magma*** increases magma viscosity leading to the ***development of a cap.***

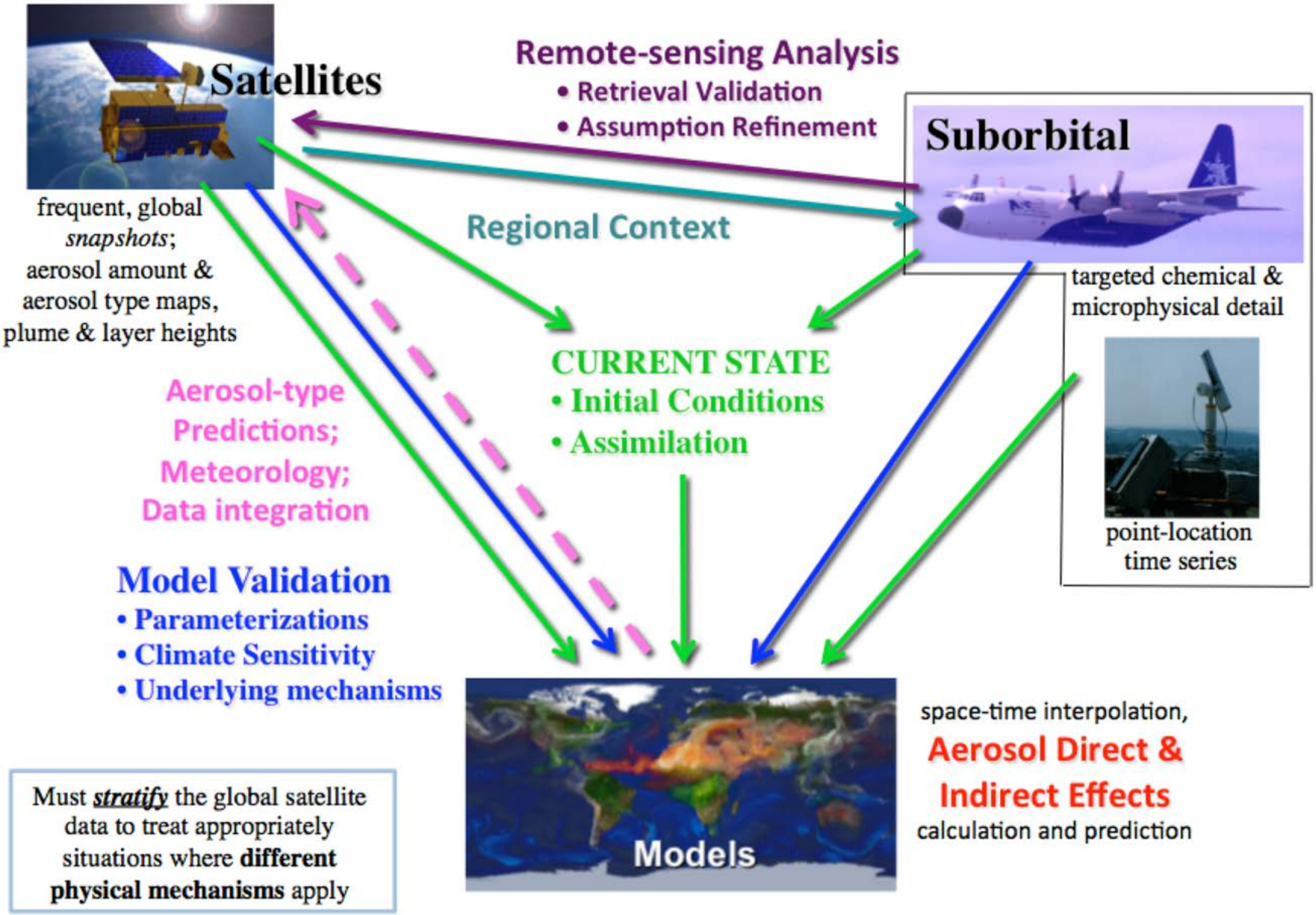
Small sulfate/water plumes tend to occur that are ***less conducive*** with MISR observations.

Lava flow development ceases.

Picking a research topic at a professional level

- *What are the strengths and limitations of the data*
- What are the leading scientific questions
- What has been done already
- What important questions remain
- ***What are the strengths and limitations of the data***
- What tools and skills can you bring to the table
- ***What really interests you***

New Ideas – Multi-Instrument, Model



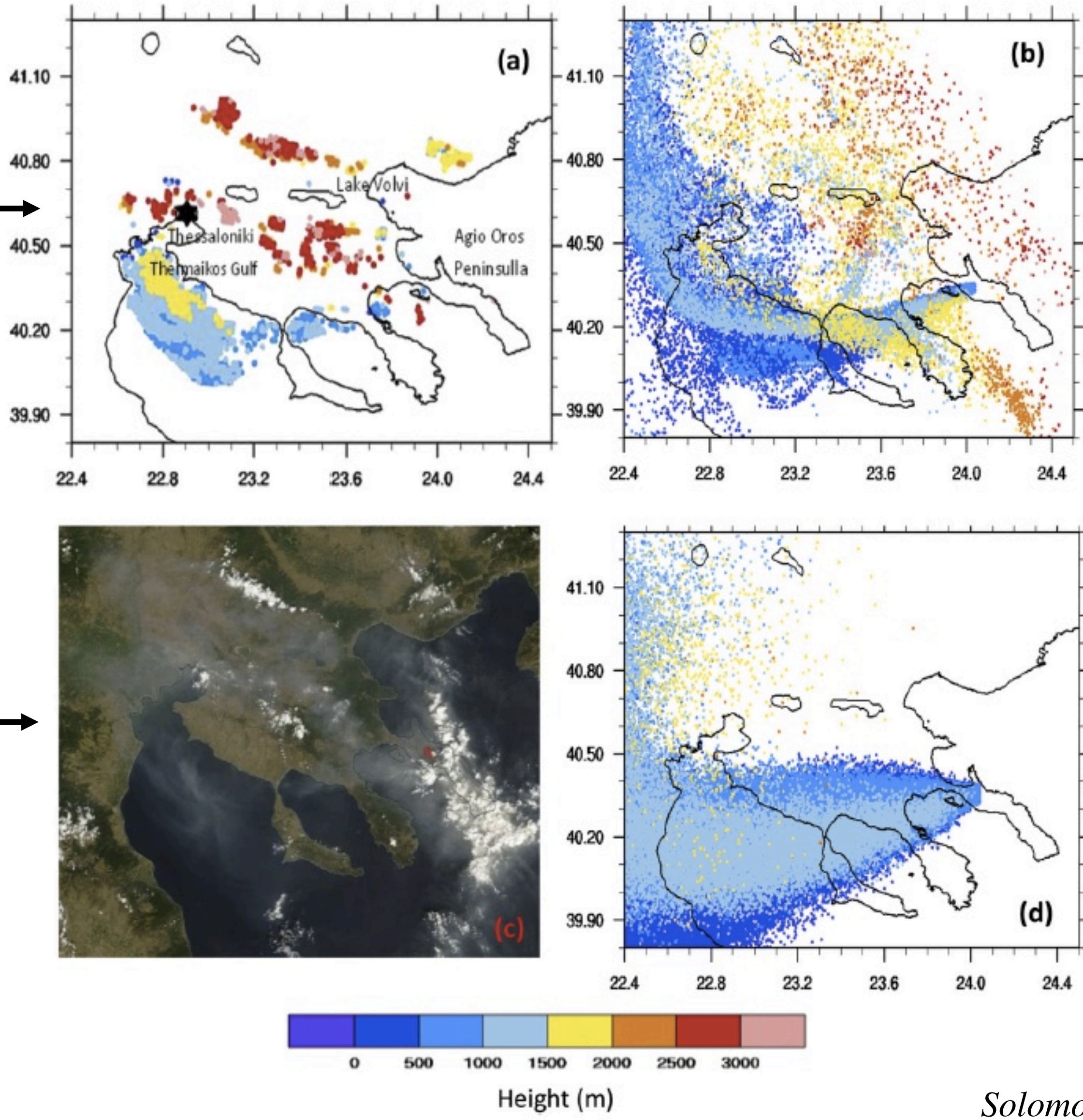
Adapted from: Kahn, Survy. Geophys. 2012

New Ideas – Multi-Instrument, Model

Wildfire Plume Heights, in Greece 09 August 2012

MISR
Plume Heights

Agion_Oros
S4P
Model
simulated smoke

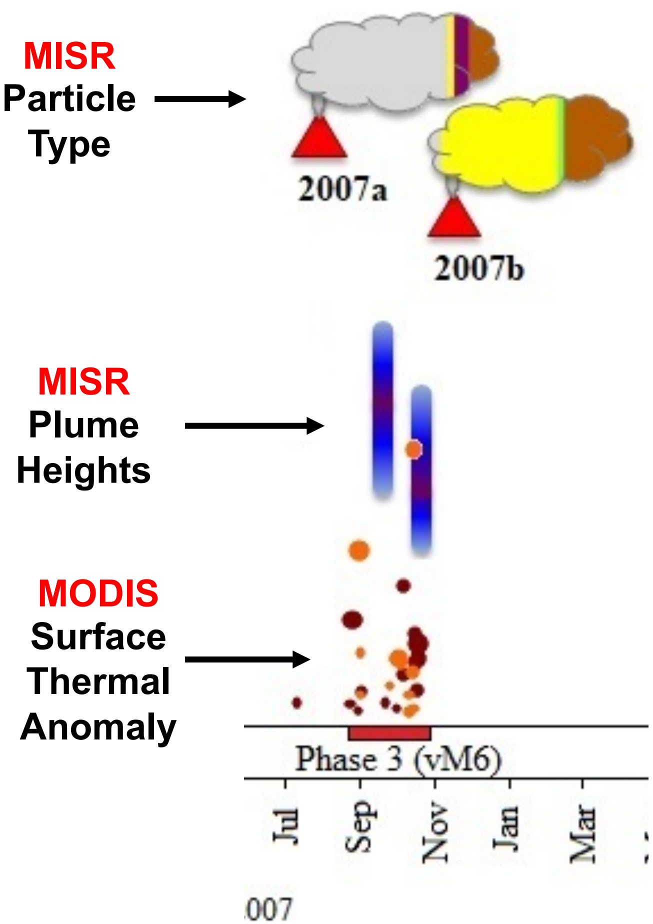


MODIS
Context Image showing smoke distribution

Agion_Oros
S50P
Model
simulated smoke

Solomos et al., Atmosph. Env. 2015

New Ideas – Multi-Instrument, Model

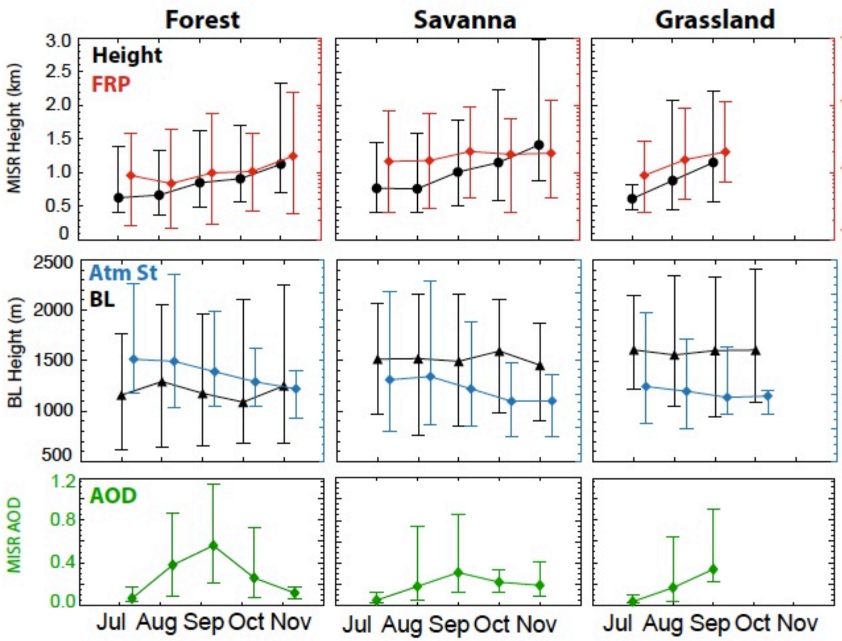


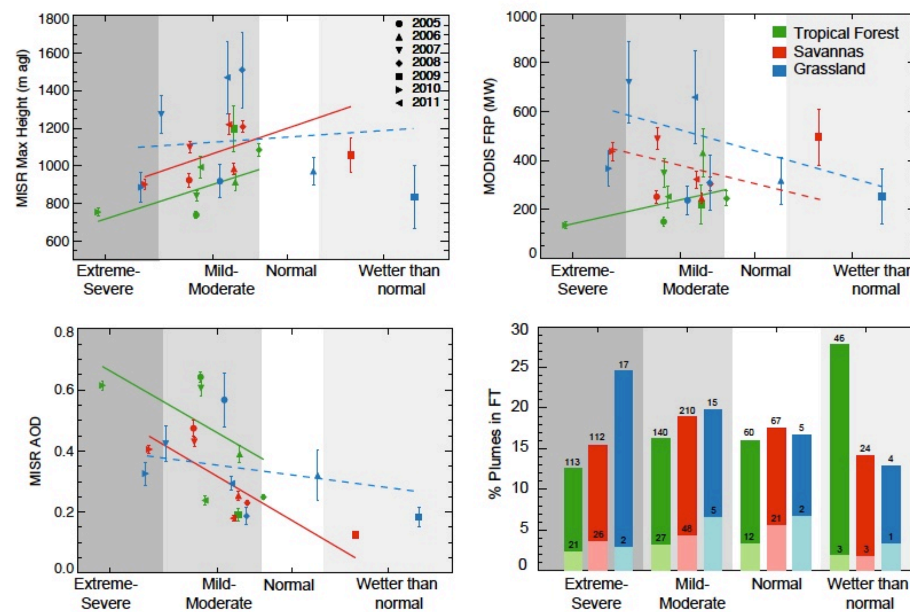
- Eruption phase 3 – August – November 2007
  - Plumes identified near the beginning of the phase
  - ***Early plume*** – ***ash-rich***, with moderate angularity and strong absorption
  - ***Later plume*** – ***High fraction of 'sulfate'*** proxy accompanied by medium angular particles (identified in the analysis of Bardarbunga, Iceland 2014 eruption).
- ***Initial eruptions*** generated by ***viscous material*** possibly in the form of a lava dome.
- ***Depressurization*** of the system ***caused upwelling of volatile-rich magma*** producing more sulfate containing plumes
  - ***Thermal anomalies*** indicate the rapid extension and intensity of flow features indicative of ***less viscous magma***.

Flower & Kahn, J. Volcanology 2017

If You Don't Have A "New" Idea – Regional Study

Biomass burning smoke heights over the Amazon observed from space





Seasonal Cycle of 5 parameters, stratified by ***Vegetation Type***

MISR Plume Height, MODIS FRP, Model BL Height & Atm. Stability MISR AOD

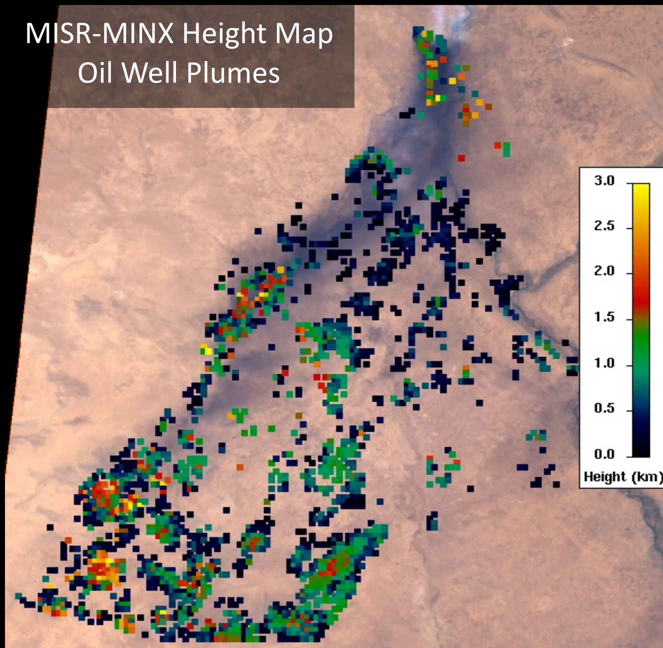
Interannual patterns of 4 parameters, stratified by ***Drought Index***

MISR Plume Height, MODIS FRP, MISR AOD, % in Free Troposphere

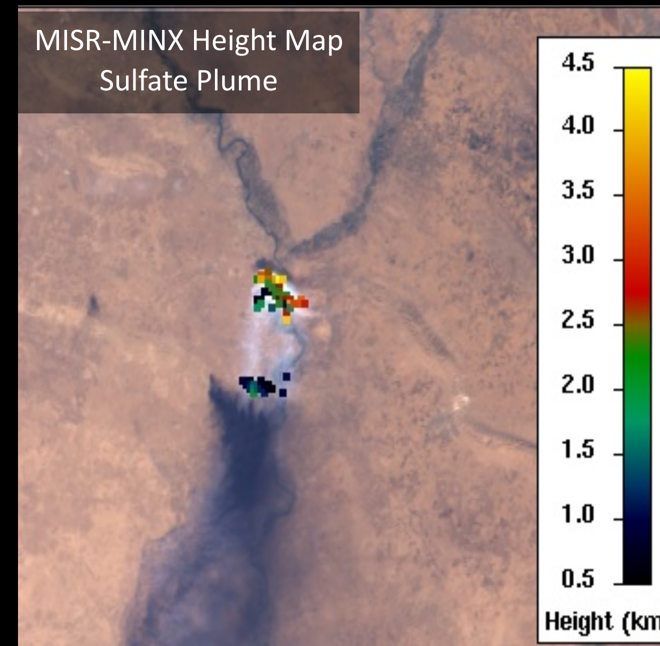
Gonzalez-Alonso ACP 2018, submitted

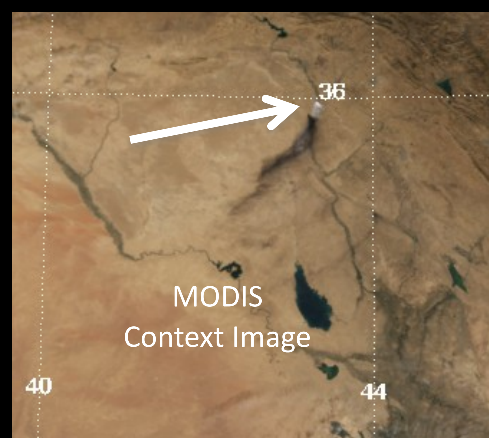
Iraq's Mishraq Sulfur Plant and Oil Well Smoke Plume Heights

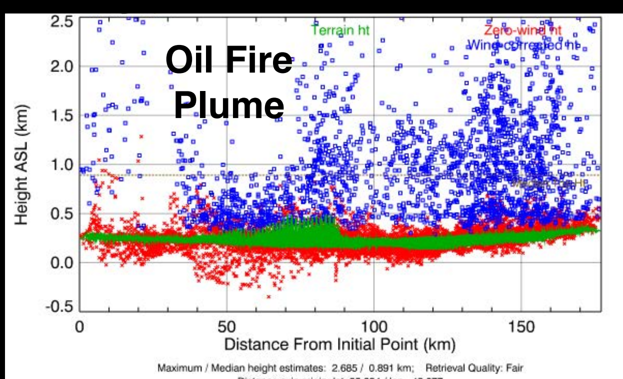
MISR Active Aerosol Plume-Height (AAP) Project 21 October 2016

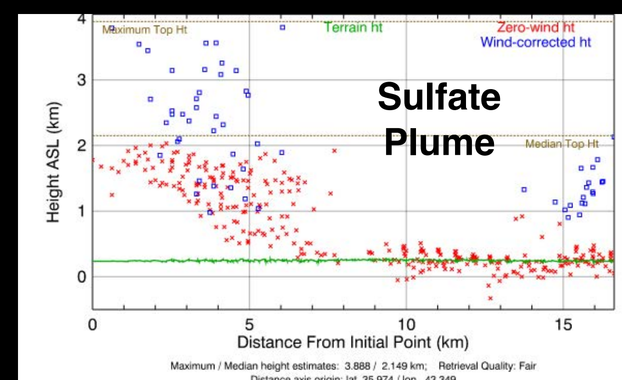


Black smoke emanates from oil-well fires and white smoke from a burning sulfate plant, during the recapture of Mosul in northern Iraq in October 2016. The sulfate plume remained within the near-surface boundary layer, whereas some of the oil-fire plumes might have escaped into the free troposphere, and traveled much further downwind.









Zero-wind & Wind-Corrected
MISR Height Profiles
Downwind from Near-source

***R. Kahn*, T. Kucsera / NASA GSFC**
T. Canty, R. Bolt, CJ Vernon / U. Maryland